

LONG-TERM EFFECTS OF PHYSICOCHEMICAL AMENDMENTS ON PLANT PERFORMANCE AT A BENTONITE MINESITE IN THE NORTHERN GREAT PLAINS

by
D.J. Dollhopf, R.B. Rennick and S.C. Smith

Reclamation Research Unit
Montana State University
Bozeman, Montana 59717

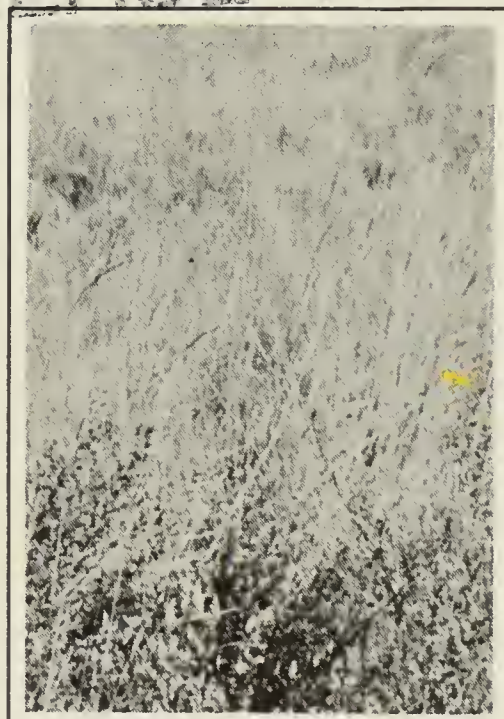
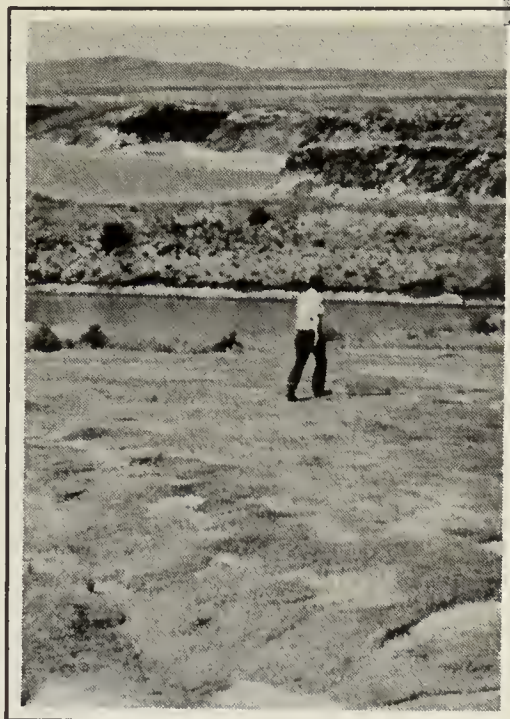
STATE DOCUMENTS COLLECTION

MAR 20 1990

MONTANA STATE LIBRARY
1515 E. 6th AVE.
HELENA, MONTANA 59620



PLEASE RETURN



Prepared for
The Montana Department of State Lands, Montana Abandoned Mine Reclamation Bureau, Helena, MT
Reclamation Research Publication 88-02
1988

live
1924
AUG 23 1999

MONTANA STATE LIBRARY
S 631.42 M41Lep 1988 c.1 Dollhopf
Long-term effects of physiochemical amen
3 0864 00066981 5

DISCLAIMER

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Montana Department of State Lands.

Reference to specific equipment or trade names in this report is made to facilitate understanding and does not imply endorsement by either Montana State University or the Montana Department of State Lands.

ACKNOWLEDGEMENTS

The authors express their thanks to the Abandoned Mine Reclamation Bureau, Montana Department of State Lands for providing financial support, and to the American Colloid Company for providing access to the research site and technical support. In particular, thanks to Mr. Richard Juntunen, Chief, Abandoned Mine Reclamation Bureau, Montana Department of State Lands, and to Steve MacIntosh of American Colloid, Belle Fourche, South Dakota.

The authors also thank Dr. Frank Munshower and Dr. William Inskeep, both from Montana State University, and Dr. Gerald Schuman, USDA, Cheyenne, Wyoming for their review comments on this report.

PREFACE

Dr. Douglas J. Dollhopf (Soil Scientist) was the Principal Investigator, Robert B. Rennick was the Reclamation Plant Ecologist, and Steven C. Smith was a Graduate Research Assistant.

The U.S. Bureau of Land Management funded this investigation in 1980 for a several year period. Unfortunately, the U.S. BLM had a change in funding priorities and this project was terminated shortly after the experimental design had been implemented. For this reason, no data were collected from 1980 to 1986.

It was curiosity that caused us to return to the test site for the first time in 1986. It was apparent that several treatments provided excellent land reclamation and a wealth of information was available. The Montana Department of State Lands then provided funding to complete this research.



REPORT DOCUMENTATION PAGE

Title and Subtitle Long-term Effects of Physicochemical Amendments on Plant Performance at a Bentonite Minesite in the Northern Great Plains	Report Date 1988
Authors D.J. Dollhopf, R.B. Rennick and S.C. Smith	Performing Organization Report No. RRU 88-02
Performing Organization Name and Address Reclamation Research Unit Montana State University 106 Linfield Hall Bozeman, MT 59717 (406) 994-4821	Contract No.
Sponsoring Organization Name and Address Montana Abandoned Mine Reclamation Bureau Montana Department of State Lands Capitol Station Helena, MT 59620 (406) 444-2074	Type of Report and Period Covered Final Report 1980-1986
Abstract The effects of surface manipulation (straw mulch, gouging), chemical amendments (H_2SO_4, $CaCl_2$, gypsum), organic amendments (woodchips, manure), topsoil and irrigation were evaluated from 1980 to 1986 on abandoned bentonite mined lands located near Belle Fourche, SD. Minesoils treated with H_2SO_4 in combination with either gypsum or manure, and minesoils treated with $CaCl_2$ plus gypsum, had SAR and EC significantly reduced from 38 to 8 and 7.0 to 1.8 mmhos/cm, respectively. These treatments had plant production significantly greater (1936 to 3169 kg/ha) compared to the control (416 kg/ha). Application of woodchips and surface gouging had no effect on either minesoil SAR or plant production compared to the control. Daily sprinkler irrigation for 20 days after seeding did not enhance plant establishment without topsoil. Applied topsoil (10 cm, SAR 1) quickly became sodic (SAR 27) and had plant production not significantly different compared to the control. Western, tall, and thickspike wheatgrass were the most successful seed species, however, natural plant invasion was substantial. The low cost industrial wastes phosphogypsum and $MgCl_2$ brine were evaluated beginning in 1986 on test plots adjacent to those established in 1980. After 16 months, $MgCl_2$ and phosphogypsum significantly reduced minesoil SAR (21.3 and 24.5) compared to the control. By the second growing season, mean plant production on $MgCl_2$ treated plots (2717 kg/ha) was greater than on phosphogypsum treated plots (1753 kg/ha).	



Digitized by the Internet Archive
in 2016

<https://archive.org/details/longtermeffectso1988doll>

TABLE OF CONTENTS

<u>DISCLAIMER</u>	i
<u>ACKNOWLEDGEMENTS</u>	i
<u>PREFACE</u>	i
<u>REPORT DOCUMENTATION PAGE</u>	ii
<u>TABLE OF CONTENTS</u>	iii
<u>LIST OF TABLES</u>	vi
<u>LIST OF FIGURES</u>	x
1.0 INTRODUCTION	1
1.1 OBJECTIVES	2
2.0 CONCLUSIONS	3
2.1 AMENDMENTS EFFECTS ON MINESOIL PHYSICOCHEMISTRY	3
2.2 AMENDMENT EFFECTS ON VEGETATION DEVELOPMENT	4
2.3 RECLAMATION WITH PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE	5
3.0 RECOMMENDATIONS	7
4.0 OVERVIEW OF BENTONITE MINE LAND RECLAMATION	9
4.1 BENTONITE ORIGIN AND GEOLOGIC ASSOCIATION	10
4.2 PHYSICOCHEMICAL PROPERTIES OF BENTONITE SPOIL	11
4.3 BENTONITE MINING AND PROCESSING	14
4.4 BENTONITE MINELAND RECLAMATION	15
4.4.1 <u>Reclamation Difficulties</u>	15
4.4.2 <u>Biological Consequences of No Reclamation</u>	16
4.5 PREVIOUS BENTONITE RECLAMATION INVESTIGATIONS	16
4.5.1 <u>Initial Bentonite Reclamation Research</u>	16
4.5.2 <u>Recent Bentonite Reclamation Research</u>	17
5.0 EFFECTS OF H₂SO₄, CaCl₂, GYPSUM, MANURE, WOODCHIPS, TOPSOIL, GOUGING, MULCHING AND EMERGENCE IRRIGATION ON MINESOIL PHYSICOCHEMISTRY AND VEGETATION DEVELOPMENT	20
5.1 METHODS AND MATERIALS	20
5.1.1 <u>Site Description</u>	20
5.1.2 <u>Experimental Design and Implementation</u>	20
5.1.3 <u>Plant Sampling Methodology</u>	23
5.1.4 <u>Minesoil Sampling and Analysis Methods</u>	25
5.2 RESULTS	27
5.2.1 <u>Minesoil Physicochemical Characteristics</u>	27

TABLE OF CONTENTS (Cont.)

5.2.2	<u>Effects of Chemical and Physical Amendments on Bentonite Minesoils</u> . . .	29
5.2.2.1	<u>Sodicity</u>	29
5.2.2.2	<u>Salinity</u>	34
5.2.2.3	<u>Acidity</u>	38
5.2.2.4	<u>Infiltration</u>	43
5.2.3	<u>Vegetation Responses to Chemical and Physical Bentonite Minesoil Amendments</u> .	49
5.2.3.1	<u>Initial Plant Performance - 1980</u>	49
5.2.3.2	<u>Plant Performance After Seven Growing Seasons - 1986</u>	50
5.2.3.3	<u>Vegetation Response to Minesoil Amendments</u>	53
5.3	<u>DISCUSSION.</u>	56
5.3.1	<u>Reclamation with Chemical Amendments</u> . .	56
5.3.2	<u>H₂SO₄</u>	58
5.3.3	<u>High pH Problems</u>	61
5.3.4	<u>Required Time Period for Chemical Amendment Reclamation</u>	62
5.3.5	<u>Emergence Irrigation</u>	63
5.3.6	<u>Topsoil Use and Sodication</u>	63
5.3.7	<u>Application of H₂SO₄</u>	64
5.3.8	<u>Erosion Control</u>	65
5.4	<u>SUMMARY</u>	65
6.0	<u>EFFECTS OF INDUSTRIAL WASTE PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE BRINE ON MINESOIL PHYSICO-CHEMISTRY AND VEGETATION DEVELOPMENT</u>	67
6.1	<u>CHARACTERISTICS OF PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE BRINE</u>	67
6.1.1	<u>Phosphogypsum</u>	67
6.1.2	<u>Magnesium Chloride</u>	68
6.2	<u>METHODS AND MATERIALS</u>	69
6.2.1	<u>Field Plot Design</u>	69
6.2.2	<u>Amendments and Application Rate Determinations</u>	70
6.2.3	<u>Field Plot Implementation</u>	74
6.2.4	<u>Minesoil Physicochemical Analysis</u> . . .	74
6.2.5	<u>Infiltration Rate Study</u>	76
6.2.6	<u>Vegetation Monitoring</u>	77
6.2.7	<u>Root Biomass Study</u>	77
6.2.8	<u>Statistical Analysis</u>	78
6.3	<u>RESULTS AND DISCUSSION</u>	78
6.3.1	<u>Amendment Trace Element Concentrations</u> .	78
6.3.2	<u>Minesoil Physicochemical Characteristics</u>	80
6.3.3	<u>Effects of Chemical Amendments on Minesoil Physicochemical Properties</u> . .	80

TABLE OF CONTENTS (Cont.)

6.3.3.1	<u>Minesoil Sodium Adsorption Ratio (SAR)</u>	80
6.3.3.2	<u>Minesoil Electrical Conductivity (EC)</u>	87
6.3.3.3	<u>Minesoil pH</u>	92
6.3.3.4	<u>Saturation Percentage</u>	93
6.3.4	<u>Minesoil Infiltration Rate Study</u>	94
6.3.5	<u>Vegetation Development</u>	96
6.3.5.1	<u>Seedling Density</u>	96
6.3.5.2	<u>Canopy Cover</u>	98
6.3.5.3	<u>Above Ground Plant Production</u>	98
6.3.5.4	<u>Root Biomass</u>	99
6.4	<u>SUMMARY</u>	100
6.4.1	<u>Minesoil Physicochemical Response</u>	100
6.4.2	<u>Vegetation Response</u>	101
7.0	AMENDMENT COSTS FOR RECLAMATION OF ABANDONED BENTONITE MINESOILS	103
7.1	CHEMICAL AMENDMENTS	103
7.2	ORGANIC AND SURFACE AMENDMENTS	103
8.0	LITERATURE CITED	110
9.0	APPENDICES	120
	APPENDIX A	121
	Plant Performance Data	122
	APPENDIX B	124
	Minesoil Physical and Chemical Data	125

LIST OF TABLES

Table 1.	Seed mixture and rates, Belle Fourche, SD, April 1980.	24
Table 2.	Minesoil physicochemical analysis procedures.	26
Table 3.	Physicochemical characteristics of two composite minesoil samples used for this investigation located near Belle Fourche, SD.	28
Table 4.	Minesoil modulus of rupture, hydraulic conductivity and clay mineralogy.	28
Table 5.	Mean 1980 SAR values, Belle Fourche, SD.	30
Table 6.	Mean SAR values compared between years, Belle Fourche, SD.	31
Table 7.	Mean 1986 SAR values, Belle Fourche, SD.	35
Table 8.	Mean 1980 EC (mmhos/cm), Belle Fourche, SD.	36
Table 9.	Mean EC (mmhos/cm) values compared between years, Belle Fourche, SD.	37
Table 10.	Mean 1986 EC (mmhos/cm) values, Belle Fourche, SD.	39
Table 11.	Mean 1980 pH values, Belle Fourche, SD.	42
Table 12.	Mean pH values compared between years, Belle Fourche, SD.	44
Table 13.	Mean 1986 pH values, Belle Fourche, SD.	47
Table 14.	Simulated rainfall infiltration over a 30 minute period for bentonite minesoils.	48
Table 15.	Simulated rainfall infiltration rate after 30 minutes in bentonite minesoils.	48
Table 16.	Classification of infiltration rates (Soil Conservation Service, 1951).	49

LIST OF TABLES (Cont.)

Table 17.	Plant density by treatment and life form, July 1980, Belle Fourche, SD.	50
Table 18.	Mean aboveground production and canopy cover by life form, July 1986, Belle Fourche, SD.	51
Table 19.	Mean percent canopy coverage by species and treatments, June 1986, Belle Fourche, SD.	52
Table 20.	Root biomass (g/1000 g of soil), June 1986, Belle Fourche, SD.	57
Table 21.	Comparison of calcium, magnesium and sodium water extractable levels in minesoils from 1980 to 1986	61
Table 22.	Chemical Amendment and nitrogen fertilizer rate treatments at the Belle Fourche site.	70
Table 23.	Representative values for unamended spoil chemistry at the Belle Fourche site.	72
Table 24.	Plant species seeded in Spring, 1986 at the Belle Fourche site.	74
Table 25.	Trace element total concentrations in phosphogypsum and magnesium chloride brine	79
Table 26.	Unamended spoil chemical characteristics over time at the Belle Fourche site.	81
Table 27.	Spring, 1986 physical analysis (%) of unamended spoil at the Belle Fourche site. . .	82
Table 28.	Fall, 1986 minesoil SAR values at the Belle Fourche site.	82
Table 29.	Summer, 1987 minesoil SAR values at the Belle Fourche site.	83
Table 30.	Minesoil SAR values over time at the Belle Fourche site.	84
Table 31.	Fall, 1986 minesoil electrical conductivity (EC) values at the Belle Fourche site.	88

LIST OF TABLES (Cont.)

Table 32.	Summer, 1987 minesoil electrical conductivity (EC) values at the Belle Fourche site.	89
Table 33.	Minesoil electrical conductivity (EC) values over time at the Belle Fourche site.	89
Table 34.	Minesoil pH values over time at the Belle Fourche site.	92
Table 35.	Summer, 1987 minesoil saturation percentage at the Belle Fourche site.	93
Table 36.	Summer, 1987 minesoil infiltration rates over time at the Belle Fourche site.	94
Table 37.	Seedling density (plants/m ²) in 1986, by chemical amendment at the Belle Fourche. SD. .	97
Table 38.	Seedling density (plants/m ²) in 1986, by fertilizer rate at the Belle Fourche site	97
Table 39.	Summer, 1987 percent canopy cover at the Belle Fourche site.	98
Table 40.	Summer, 1987 plant production (kg/ha) at the Belle Fourche site.	99
Table 41.	Summer, 1987 minesoil root biomass (g/1000 g soil) at the Belle Fourche site . . .	100
Table 42.	Specifications for chemical amendments on bentonite mine land.	104
Table 43.	Specifications for physical amendments on bentonite mine land.	105
Table 44.	Seed mixture specifications for bentonite mine land.	108
Table 45.	Mean aboveground production (kg/ha) by plant class and treatment, June 1986, Belle Fourche, SD.	122

LIST OF TABLES (Cont.)

Table 46.	Mean percent canopy coverage by plant class and treatment, June 1986, Belle Fourche, SD.	123
Table 47.	Fall, 1986 minesoil chemical analysis at the Belle Fourche site.	125
Table 48.	Summer, 1987 physicochemical analysis at the Belle Fourche site.	126

LIST OF FIGURES

Figure 1.	Research site location 11 km (7 miles) northwest of Belle Fourche, South Dakota.	1
Figure 2.	Bentonite-bearing formations and units from which bentonite is mined in the Powder River Basin.	12
Figure 3.	Precipitation data for Belle Fourche, SD.	21
Figure 4.	Experimental design implemented in 1980 at Belle Fourche, SD.	22
Figure 5.	Spoil profile SAR for amendment treatments in 1980 and 1986, Belle Fourche, SD.	32
Figure 6.	Spoil profile EC (mmhos/cm) for amendment treatments in 1980 and 1986, Belle Fourche, SD.	40
Figure 7.	Spoil profile pH for amendment treatments in 1980 and 1986, Belle Fourche, SD.	45
Figure 8.	Aboveground production by plant class and treatment, June 1986, Belle Fourche, SD.	54
Figure 9.	Canopy coverage by plant class and treatment, June 1986, Belle Fourche, SD.	55
Figure 10.	1986 Field plot design at the Belle Fourche site.	71
Figure 11.	Minesoil (0-5 cm) SAR change over time at the Belle Fourche site.	85
Figure 12.	Minesoil (5-10 cm) SAR change over time at the Belle Fourche site.	85
Figure 13.	Minesoil (10-20 cm) SAR change over time at the Belle Fourche site.	86
Figure 14.	Minesoil (20-35 cm) SAR change over time at the Belle Fourche site.	86

LIST OF FIGURES (Cont.)

Figure 15.	Minesoil (0-5 cm) electrical conductivity (EC) change over time at the Belle Fourche site.	90
Figure 16.	Minesoil (5-10 cm) electrical conductivity (EC) change over time at the Belle Fourche site.	90
Figure 17.	Minesoil (10-20 cm) electrical conductivity (EC) change over time at the Belle Fourche site.	91
Figure 18.	Minesoil (20-35 cm) electrical conductivity (EC) change over time at the Belle Fourche site.	91
Figure 19.	Minesoil infiltration rates over time at the Belle Fourche site.	96

1.0 INTRODUCTION

The tri-state region of Montana, South Dakota, and Wyoming contains approximately 90 to 95 percent of the world's commercially minable deposits of high-grade sodium bentonite (Romo 1981). Montana possesses the greatest reserves with 270 million metric tons (Ampian 1985). Mining was widespread during the mid 1900's before reclamation laws were enacted. As a result, tens-of-thousands of acres of bentonite disturbances were abandoned on the Northern Great Plains. Because of the adverse physicochemical properties of bentonitic spoils, vegetation fails to invade from surrounding native rangeland. Factors which typically inhibit revegetation are saline-sodic conditions, high smectite clay content, and impermeable surface crusts. Many old bentonite spoils remain totally unvegetated, even 50 years after mining. Land in this condition represents a significant loss of livestock productivity.

In 1980, the U.S. Bureau of Land Management funded a multi-year investigation intended to develop reclamation techniques for these abandoned lands. Three months after test plots had been established near Belle Fourche, SD (Figure 1), a change in funding priorities caused BLM to terminate this investigation. It was curiosity that caused us to return to the test plots for the first time in 1986. It was apparent that several treatments provided excellent land reclamation and these test plots contained a wealth of information. The Montana Abandoned Mine Reclamation Bureau provided funding to complete this research. For this reason, no data are presented between the years 1980 and 1986.

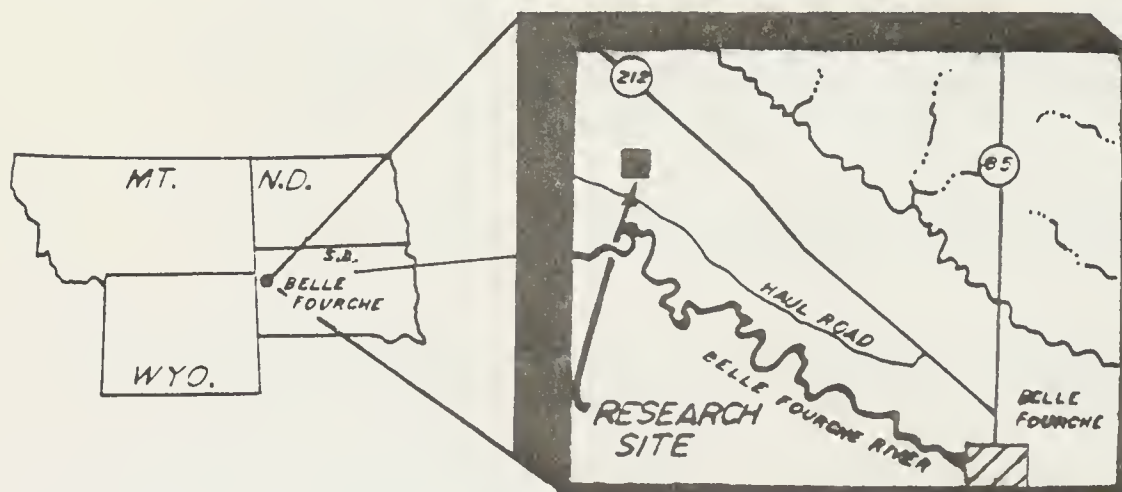


Figure 1. Research site location 11 km (7 miles) northwest of Belle Fourche, South Dakota.

1.1 OBJECTIVES

The purpose of this research project was to develop reclamation technology for abandoned bentonite mine lands in the Northern Great Plains. Specific objectives of this study were to:

- evaluate the effectiveness of sulfuric acid, calcium chloride, gypsum, phosphogypsum, magnesium chloride brine, woodchips, manure, topsoil, surface gouging, straw mulch and emergence irrigation for reclamation of these minesoils; and
- determine plant performance characteristics on amended minesoils.

2.0 CONCLUSIONS

The effects of surface manipulation (chiseling, gouging), chemical amendments (H_2SO_4 , CaCl_2 , gypsum), organic amendments (woodchips, manure), topsoil and irrigation were evaluated on abandoned bentonite mined lands from 1980 to 1986. Untreated minesoils were sodic (SAR 33-38), clayey (60-68%), and dominated by smectite clay mineralogy.

2.1 AMENDMENT EFFECTS ON MINESOIL PHYSICOCHEMISTRY

- 1) Minesoils treated with H_2SO_4 in combination with either gypsum or manure and minesoils treated with CaCl_2 plus gypsum had sodic conditions significantly reduced from a sodium adsorption ratio (SAR) of approximately 38 to 8 during a six year period.
- 2) These same treatments significantly decreased mine-soil electrical conductivity (EC) from approximately 7.0 to 1.8 mmhos/cm.
- 3) Significant decreases in minesoil SAR were confined to the 0-20 cm depth increment. Significant decreases in EC were present in the 0-10 cm zone. Incorporation of amendments with a chisel plow was limited to approximately the 20 cm depth.
- 4) Neither manure by itself nor woodchips significantly decreased SAR or EC in minesoils compared to the control.
- 5) Surface pitting (gouging) had no effect on either SAR or EC.
- 6) After 10 cm of topsoil (SAR 1) was applied in 1980, it had become sodic (SAR 27) by 1986. Sodication of the topsoil was attributed to the upward diffusion of salts from spoils into topsoil.
- 7) Sprinkler irrigation of these amended minesoils for a 20 day period after seeding had no effect on either SAR or EC.
- 8) The mechanism by which H_2SO_4 plus gypsum reduced SAR was unique and not often presented in soil science.
 - No alkaline earth carbonates were present in the minesoil, therefore, H_2SO_4 could not react to produce gypsum.
 - Application of H_2SO_4 did not increase the solubility of native or applied gypsum.

- Consequently, there was no soluble source of calcium to displace sodium from the cation exchange sites.
 - The H_2SO_4 solubilized aluminum and iron from silicate clay minerals. Both Al^{3+} and $\text{Al}(\text{OH})^{2+}$ served to displace Na^+ from cation exchange sites, which caused a decreased SAR.
- 9) Minesoils treated with H_2SO_4 in 1980 (pH 7.1-7.3) were very acidic (pH 4.3-5.4) in 1986 in the 0-10 cm depth. This was due to aluminum displacing sodium on the cation exchange sites.
 - 10) Both manure and topsoil treated minesoils had undesirable pH levels (>8.5) to the 10 cm depth. The increased pH was likely due to sodium hydrolysis.
 - 11) Minesoils treated with gypsum plus CaCl_2 , manure alone and woodchips had a significantly greater infiltration rate (moderately rapid, >6.3 cm/hr) compared to the control (2.8 cm/hr). All other treatments were not significantly different compared to the control or infiltrated significantly less than the control.

2.2 AMENDMENT EFFECTS ON VEGETATION DEVELOPMENT

- 12) Three months after seeding in spring 1980, plant density was notably greater in woodchip and topsoil treated minesoils. Minesoils treated with gypsum, H_2SO_4 , and CaCl_2 had little or no plant growth.
 - These results indicated that chemical amendments will not provide a suitable plant establishment environment three months after seeding, meaning that chemical mitigation of the sodic problem was not immediate.
- 13) Surface pitting (gouging) and manure application did not enhance plant density compared to the control three months after seeding.
- 14) Emergence irrigation did not enhance plant density compared to the control. Emergence irrigation in combination with H_2SO_4 and gypsum did not improve density compared to the same chemical application alone. When these sodic minesoils were topsoiled, emergence irrigation increased plant density by 40% the first growing season. This indicates irrigation for 20 days after seeding has merit when the root zone has no physical or chemical limitations.

Without topsoil, emergence irrigation did not enhance first year plant density.

- 15) After seven growing seasons, the manure treatments (i.e. vertical mulch, surface applied, H_2SO_4 combination) and gypsum in combination with either H_2SO_4 or CaCl_2 had plant production significantly greater (1936 to 3169 kg/ha) compared to the control (416 kg/ha). There was no difference between manure tilled into the minesoil surface (30 cm) or placed in trenches (vertical mulching) to the 90 cm depth.
- 16) Minesoils treated with either woodchips or topsoil had plant productivity that was not significantly different compared to the control. Mean plant production on woodchip treated plots was less than on plots treated with combinations of H_2SO_4 , CaCl_2 , gypsum and manure, but these differences were not significant except for the H_2SO_4 plus manure treatment.
- 17) Surface pitting (gouging) had no effect on plant performance compared to the control into the seventh growth season.
- 18) Although a straw mulch crimped into the minesoil surface helped increase first year plant density, there was no significant difference between mulch or no mulch after seven growing seasons.
- 19) "Rosana" western wheatgrass was the most successfully seeded species, followed by tall and slender wheatgrass. Seeded species comprised 65% of the canopy coverage, but invading species were commonly encountered.
- 20) Although applications of H_2SO_4 decreased minesoil pH to low levels (4.3-5.4), this decrease had no effect on plant performance. Similarly, increased pH levels (8.3-8.9) that resulted from manure application and topsoil sodication had no effect on plant performance.

2.3 RECLAMATION WITH PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE

Adjacent to test plots established in 1980, additional test plots were constructed in 1986 to evaluate two low cost chemicals that are industrial waste products, phosphogypsum and MgCl_2 brine. The effects of these amendments on site reclamation was evaluated for only 16 months and results must be considered preliminary.

- 21) Although phosphogypsum had enriched levels of trace elements and is radioactive, these levels were sufficiently low that neither plant growth nor environmental problems would be expected. The MgCl_2 brine was not enriched with trace elements.
- 22) Application of phosphogypsum and MgCl_2 significantly reduced minesoil (0-5 cm) SAR from 33.8 to 24.5 and 21.3, respectively, during a 16 month period. At this early stage of reclamation, MgCl_2 had decreased the minesoil SAR significantly better compared to phosphogypsum.
- 23) During the first year, minesoil (0-5 cm) mean EC (8.0 mmhos/cm) increased notably with application of phosphogypsum (10.1 mmhos/cm) and MgCl_2 (15.9 mmhos/cm). The EC is expected to eventually decrease well below 8.0 mmhos/cm as the SAR decreases to a low level, and leaching is enhanced as a result of increased infiltration rate.
- 24) Following 30 minutes of simulated rainfall, minesoil infiltration rates were 2.8 cm/hr on phosphogypsum treated minesoils and 3.8 cm/hr on MgCl_2 treated minesoils, compared to 0.1 cm/hr on unamended spoil.
- 25) Plant density into the first growing season for these two treatments was 191.8 plants/m², when fertilized with 67 kg/ha nitrogen. Higher and lower rates of nitrogen decreased plant density.
 - Although these plant densities are less than those measured in 1980 on topsoil and woodchip treated minesoils, they are notably greater than densities measured on manure, CaCl_2 , gypsum and H_2SO_4 treated minesoils.
- 26) Plant canopy cover of 39% on MgCl_2 treated minesoils was significantly greater than 28% on phosphogypsum treated minesoils.
- 27) Above ground plant production was 1753 kg/ha on phosphogypsum treated plots and 2717 kg/ha on MgCl_2 treated plots. Production of pioneering (non-seeded) annual forbs comprised 60% of total production on phosphogypsum treated plots and 83% on MgCl_2 treated plots.
- 28) Based on these data, MgCl_2 performed better than phosphogypsum after two growing seasons.

3.0 RECOMMENDATIONS

- 1) Longterm reclamation of abandoned bentonite minesoils that are sodic should be accomplished with the aid of chemical amendments. Only in this manner can the sodic problem be mitigated permanently.
 - Gypsum in combination with either H_2SO_4 or CaCl_2 were the best chemical amendments.
 - H_2SO_4 has a much lower cost compared to CaCl_2 which makes it the amendment of choice in combination with gypsum.
 - Although H_2SO_4 was not tested alone, these results indicate that calcium from gypsum did little to improve the minesoil chemistry. Application of H_2SO_4 alone may be sufficient to reduce the sodic condition of these minesoils.
 - If CaCl_2 is selected, half of the amendment field requirement can be composed of gypsum or phosphogypsum which are much less costly.
 - Both gypsum and phosphogypsum should not be applied alone to remediate a sodic problem, since their solubility may be too low to be effective during the early years of reclamation.
 - MgCl_2 may be the amendment of the future with the best cost:benefit ratio. However, after only 16 months of field study, results are too preliminary to make an accurate recommendation.
 - The calculated amendment field application rate must include factors for purity, proportion greater than 60 mesh, and be increased 25% to account for the lack of quantitative displacement.
- 2) On near level postmine landscapes, application of only chemical amendments may be adequate for successful reclamation. However, since chemical amendments may not remediate the sodic problem immediately, sloped areas should be stabilized with both pitting (ditcher-diker or gouging) and woodchips, manure or topsoil. These treatments will help control erosion and enhance first year plant density.
- 3) Less than 30 cm of topsoil should not be placed over sodic bentonite mine spoils. Most of the topsoil will rapidly sodicate resulting in a permanent loss in land capability.

- If less than 30 cm of topsoil is used, it should be in combination with chemical amendments to prevent topsoil sodication.
- 4) Stockpiles of manure and woodchips in the project area should be inventoried. Manure applications provided excellent plant performance, but availability and cost feasibility at rates as high as 224 mt/ha (100 T/A) are unknown.
 - 5) Land reclamationists in the Northern Great Plains have neither the experience nor the equipment to apply concentrated H_2SO_4 on minesoils on a large scale. Existing experience from other parts of the United States needs to be mobilized rapidly into our region, otherwise site project plans will quickly conclude application of H_2SO_4 is not feasible. One company in the southwest United States applies H_2SO_4 to 6,000 ha of land annually.
 - 6) The $MgCl_2$ brine has great potential as a low cost effective amendment. Only with continued monitoring will the merits of this amendment be determined. Both soil chemistry and plant performance in these tests plots should be evaluated in 1989.

4.0 OVERVIEW OF BENTONITE MINE LAND RECLAMATION

Montana's Open Cut Act of 1971 set guidelines for bentonite mining and reclamation. Until this time, spoils were left randomly piled adjacent to mined out pits. Significant acreages were disturbed by bentonite mining prior to enactment of controlling legislation.

The discontinuous nature of bentonite deposits resulted in numerous pits scattered over localized areas. When overburden stripping ratios became uneconomical, pits were abandoned only to be reopened a short distance away where the ratio was again acceptable. Pit size ranged from 1.2 to 4.0 hectares with depths of less than 15 meters (Hemmer et al. 1977). The pit mining method greatly increased the total area affected by mining, but left undisturbed "islands" among the spoils. Researchers at the National Academy of Science (1973) reported that as of the early 1970s, more spoils had accumulated in Montana from bentonite mining than from coal mining.

Commercial mining of sodium bentonite, often referred to as "Wyoming bentonite" began in the Northern Great Plains in the late 1800s. At that time, bentonite was used primarily in cosmetics (Wolfbauer 1976). During the mid 1900s, bentonite production reached a peak due to demand for oil well drilling fluids and taconite binding agents.

In Montana, the majority of bentonite mining occurred during the mid-1900s near Vananda, Glasgow, and Alzada. These areas were mined prior to regulations implemented under the Open Cut Act, and remain totally unreclaimed.

Adverse conditions on bentonite spoils inhibit natural vegetative invasion from adjacent rangeland. These spoils remain barren for many decades. Factors limiting plant growth often include high clay content comprised mainly of smectite mineralogy, elevated salinity and sodicity, extremes in pH, and surface crusting (Dollhopf and Bauman 1981, Sieg et al. 1983). Mixtures of overburden and bentonite, referred to as "cleanings" usually remained on the spoil surface magnifying plant growth problems (Hemmer et al. 1977, Bjugstad 1979). Sieg et al. (1982) found 25 fewer plant species and a large standing crop deficit on bentonite spoils as compared to adjacent undisturbed rangeland. Spoil materials are impermeable to water increasing runoff and accelerating erosion processes (Dollhopf and Bauman 1981). Mine pits fill with sediment laden runoff creating boggy conditions that are hazardous to livestock.

4.1 BENTONITE ORIGIN AND GEOLOGIC ASSOCIATION

Bentonite deposits in the Western U.S. are of two distinct types: Tertiary age bentonites found in Oregon, California and Nevada; and Cretaceous bentonites located in Montana, Wyoming and South Dakota (Regis 1978). Tertiary bentonites are generally of lower quality and often dominated by calcium. Limited swelling capacity and a lower commercial value result. Cretaceous bentonite is characteristically a relatively pure, sodium saturated mineral with high swelling capacity and high commercial value.

During the Cretaceous period (75 million years ago), volcanic activity occurred in Western Wyoming and Idaho. Volcanic ash was wind deposited in shallow saline seas to the east, in what is now the Northern Great Plains. Being unstable in a marine environment, this ash was altered in situ to clay minerals of the smectite group, or bentonite (Hewett 1917, Dengo 1946, Berg 1969). Evidence of volcanic ash parent material is demonstrated by the large lateral distribution of bentonite beds. In addition, the presence of glass shards and a suite of silicate minerals within the structure represent unaltered phenocrystic material of the volcanic ash (Berg 1969). While western bentonite is generally thought to be formed in marine environments, Byrne and Farvolden (1959) reported the occurrence of beds in non-marine sediments which generally contain non-dispersed bentonite.

Distribution of Cretaceous bentonite is complex due to the variability and vertical extent of the ash deposition. Sea level fluctuation provided additional complexity to the depositional environment. Prolonged ash fall events produced minable bentonite deposits while minor ash fall events resulted in numerous thinner "chalk lines" (Thorson 1976).

The major geologic materials containing commercial bentonite deposits in the tri-state area are:

- the Belle Fourche shale-Belle Fourche/Colony/Alzada area;
- the lower part of the Mitten black shale member of the Pierre shale-Belle Fourche/Colony/Alzada area;
- the Mowry shale-Belle Fourche/Colony/Alzada/Upton, Kaycee/Casper; and, the Glasgow/Malta areas;
- the Thermopolis shale-Lovell/Greybull/Warren area;
- the Frontier Formation-Lovell/Greybull/Warren area; and,

- the Bearpaw shale-Glasgow/Malta and Vananda areas.

Figure 2 graphically depicts the geologic structure of the Powder River Basin with respect to bentonite-bearing formations.

4.2 PHYSICOCHEMICAL PROPERTIES OF BENTONITE SPOIL

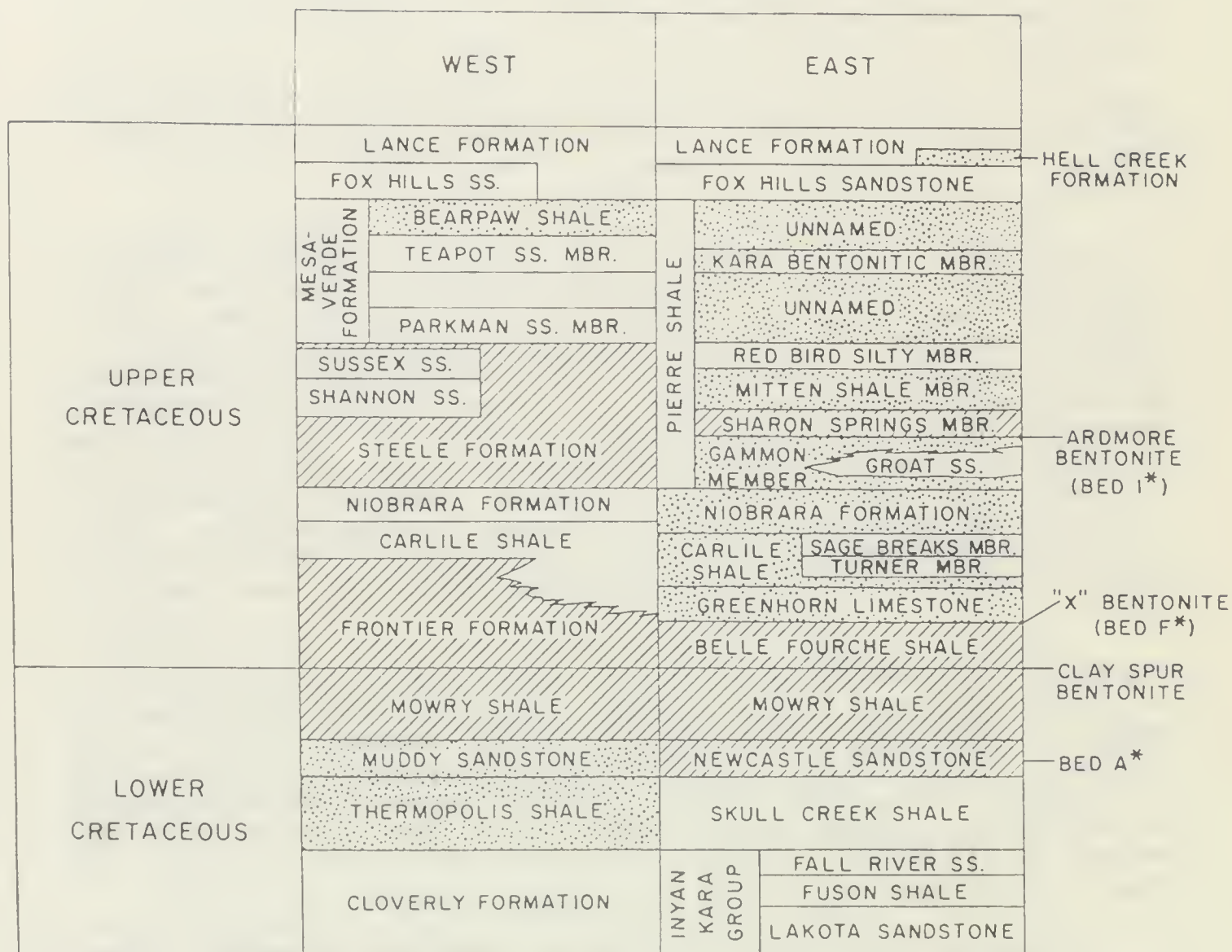
Bentonite mine spoils are dominated by weathered shales rich in 2:1 swelling clay minerals of the smectite group. Montmorillonite, a member of the smectite group, is the most abundant clay species in bentonite (Berg 1969); and is the dominant clay in bentonite spoils.

Smectite crystal units consist of an octahedral sheet sandwiched between two tetrahedral sheets. Tetrahedra are formed by a silica ion surrounded by four oxygen ions. The central octahedral is formed by an aluminum ion surrounded by six hydroxyl ions. Sharing of oxygen and hydroxyl ions produce the sheetlike 2:1 lattice structure (Grim 1968, Buckman and Brady 1969). Individual clay units stack one upon another to infinite thicknesses. Weak "Van der Waal" forces hold the crystal units loosely together forming clay particles. The weak bonds between crystal units are of key importance. Upon hydration, osmotic potential attracts water to interlayer areas producing the swelling characteristics of smectite.

Isomorphic substitution of lower valence cations within the smectite lattice structure creates excess negative charge on clay surfaces. Aluminum (Al^{3+}) commonly replaces silica (Si^{4+}) in tetrahedral layers; and either magnesium (Mg^{2+}), iron (Fe^{2+}), or lithium (Li^{+}) replace aluminum (Al^{3+}) in the octahedral layer (Regis 1978). Excess negative charge results in adsorption of positively charged soil solution cations, referred to as cation exchange capacity (CEC) (Hillel 1980, Bohn et al. 1985).

Hydrated clays form a colloidal micelle. Together, the micelle and adsorbed cations produce a diffuse electrostatic double layer between clay particles (Hillel 1980). Valence and size of adsorbed cations regulate double layer thickness, which markedly influences the magnitude of clay dispersion. Cations of particular importance are sodium (Na^{+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) because they are adsorbed in the largest quantities. Sodium dominance among adsorbed cations produced a relatively thick double layer because of large size and low valence. The thick double layer allows more water molecules between clay units enhancing swelling processes.

POWDER RIVER BASIN



EXPLANATION

-  Formations from which bentonite has been mined
-  Other formations known to contain bentonite

* Terminology of Knechtel and Patterson, 1962

Figure 2. Bentonite-bearing formations and units from which bentonite is mined in the Powder River Basin.

Flocculation is a term used to denote aggregation and structure in soil materials, while dispersion indicates a breakdown of soil structure. Flocculation/dispersion processes in smectite clay minerals are regulated by interrelationships between diffuse double layer activity, soil solution salt concentration, and the "zeta potential" developed. Zeta potential refers to strength of repulsion between clay particles. Positively charged cations act as a bridge between negatively charged clay particles decreasing the strength of repulsion.

When small sized, divalent cations such as calcium or magnesium dominate the double layer, zeta potential is reduced allowing flocculation (Buckman and Brady 1969). In a flocculated condition, the basal spacing between clay units is 9.6 angstroms (Berg 1969). A high zeta potential is promoted by sodium interlayer dominance. In this condition, multiple water molecule layers encroach interlayer areas when excess water is in the system. White and Pilcher (1959) found that sodium montmorillonite could take up in excess of 50 water molecule layers between clay units. The resultant dispersion between clay crystal units is up to 125 angstroms.

The combination of smectite clay mineralogy and high exchangeable sodium percentage (ESP) results in excessive spoil swell from clay dispersion when the system receives moisture. Swelling processes in soil materials greatly reduce hydraulic conductivity and permeability (Richards 1969, Bohn et al. 1985). Dollhopf and Bauman (1981) found that spoil from the Belle Fourche research site had extremely low hydraulic conductivity and very slow permeability.

Surface crusting caused by clay dispersion is common on bentonite minespoils. Crusting of the spoil surface adversely impacts seedling emergence and rainfall infiltration. Modulus of rupture is an index of crust strength. When modulus of rupture values exceed 1 bar, seedling emergence is often inhibited (Richards 1953). Dollhopf and Bauman (1981) reported modulus of rupture values at the Belle Fourche research site to be greater than 5.7 bars.

Hillel (1980) stated that surface crusts greatly impede water intake by a soil and have a strong effect on infiltration. Rainfall which does penetrate the surface crust infiltrates very slowly due to clay dispersion beneath the surface. The infiltration rate of water into plant growth media is critical to plant survival (Voorhees 1986). In addition, poor infiltration increases surface runoff and accelerates erosion processes.

4.3 BENTONITE MINING AND PROCESSING

Bentonite is a highly colloidal mineral consisting predominantly of smectite clays (Berg 1969). High swelling capacity and thixotropic properties make bentonite a valued industrial mineral. These characteristics are enhanced when sodium is the dominant adsorbed cation. Commercial uses of sodium bentonite are various, ranging from well drilling mud to toothpaste. Because it is used in a wide variety of industrial processes and commercial products, bentonite has been referred to as the clay of 1000 uses (Romo 1981).

The first production of bentonite in the western United States occurred in 1888 on the William Taylor ranch near Rock River, Wyoming (Knechtel and Patterson 1962). Its initial use was for cosmetics. The clay was named bentonite after the Benton formation, of Cretaceous age, from which it was mined. The first mine in the Powder River Basin was opened in 1887 near Newcastle, Wyoming. The bentonite was hand dug or plowed using horses, and dried over steel plates heated by coal or wood fires. The first claims appeared in the early 1900s. Commercial mining began northwest of the Black Hills in 1923, but only a few carloads were shipped prior to 1934. Processing began at plants in the Powder River Basin in the mid 1920s and northwest of the Black Hills in the late 1930s.

Today, there are four major areas of mining activity:

- the Belle Fourche/Colony/Alzada area;
- the Upton area;
- the Kaycee area; and
- the Lovell/Greybull/Tensleep/Warren area.

In addition, an area near Vananda, Montana was mined from 1947 to 1977, and an area near Glasgow was also mined (Hemmer et al. 1977).

In the early years of production oriented mining, draglines and later crawler tractors were used. Today, most mining is accomplished by rubber tied scrapers, although in rough terrain, crawler tractors and scrapers are used as well.

Mining is accomplished by the pit mining method. Stripped topsoil is placed in stockpiles for later use in reclamation. The overburden is then stripped and placed in adjoining pits and contoured into the surrounding landscape. In the past, the first bentonite encountered (which is a combination of overburden and bentonite, and therefore unmarketable) was left scattered in piles on the landscape. Today, reclamation requirements assure that this material is covered by overburden. The exposed bentonite is often left to "field-dry" and

then taken by truck or haul wagon to the processing plant for further drying and milling. Processing plants exist in the four major bentonite mining regions.

4.4 BENTONITE MINELAND RECLAMATION

4.4.1 Reclamation Difficulties

Prior to the enactment of reclamation laws in the late 1960s and early 1970s, virtually no reclamation was performed. As a result, mine spoils were discarded as expeditiously as possible and highwalls were not reduced. These areas are referred to as orphan spoils. Mining excavations that were not backfilled often filled with water. These impoundments are usually inaccessible to livestock because of steep shorelines or boggy conditions.

Reclamation laws required companies to develop procedures such as topsoil salvage, overburden physicochemical assessment, landscape reshaping, and revegetation. Reclaiming bentonite mine land falls into two categories:

- reclamation of orphan spoils; and
- reclaiming lands mined today.

Although there are differences in the reclamation approach to land mined before and after laws were enacted, similar problems (derived from the physicochemical nature of bentonitic soils) are usually encountered at all mine sites.

Limiting factors to the establishment of grasses, forbs and shrubs are nutrient imbalances and deficiencies, low amounts of water in the root zone due to low infiltration, high evaporation and high runoff, low availability of water due to high salt content, and direct chemical toxicity to plants (Romo 1981). Also, the swelling and shrinking of these clay soils when wetted and dried can cause physical damage to plant roots (White and Lewis 1969). These limiting factors apply ubiquitously to orphan spoils and are also important considerations to current reclamation practices. Problems brought about by today's mining methods and reclamation procedures include:

- topsoil contamination as a result of salvaging undesirable materials;
- topsoil contamination as a result of the deposition of unmarketable bentonite (i.e. "cleanings") near the surface;
- poor topsoil redistribution;

- creation of compacted seedbeds; and
- vegetation destruction by livestock grazing (Hemmer et al. 1977).

4.4.2 Biological Consequences of No Reclamation

The biological costs of not reclaiming orphan bentonite spoils and currently mined land include losses of range production (reduced animal unit months) and losses in vegetation cover, which ultimately lead to a loss of animal populations, most notably birds, mammals, insects and invertebrates. On an orphan spoil site near Alzada, Montana, Sieg et. al. (1982) found that range production was down 372 kg/ha, plant canopy cover was reduced 29 percent, and the number of small mammals and macroarthropods was reduced 19 and 163/ha, respectively, compared to unmined sagebrush grassland. There were 25 fewer plant species, and reduced vegetation diversity on spoils as compared to adjacent native rangeland. The accumulated production loss over a 30 year period would be 11,160 kg/ha (Sieg et al. 1982). The actual loss would be higher when big sagebrush, which is an important food for pronghorn antelope and sage grouse, and other forage consumed by livestock are taken into account.

4.5 PREVIOUS BENTONITE RECLAMATION INVESTIGATIONS

4.5.1 Initial Bentonite Reclamation Research

In the mid 1970s, the Montana Department of State Lands initiated an investigation designed to identify bentonite deposits and disturbances in the region, determine basic problems faced by reclamationists, and establish field plots to initially screen reclamation techniques. Deep furrowing and gouging as surface manipulations, as well as seeding rates and individual plant species response were evaluated for reclamation potential. Field plots were located at seven mine sites, representing a cross section of environmental conditions in the tri-state area of Montana, Wyoming and South Dakota. All sites had been mined in a similar manner and all were recontoured similarly prior to the implementation of field plots. After two field seasons, there was no significant improvements in vegetation production or canopy cover resulting from the surface treatments (Hemmer et al. 1977). Drill seeding rates of 13.4-16.8 kg/ha were optimal. Although revegetation efforts met with limited success, Agropyron desertorum and Agropyron dasystachyum were the most consistent producers. Adding limestone fines to the spoil material at one site did not produce any apparent improvements in plant performance. In summation, the authors recommended the chemical treatments of gypsum and calcium chloride as spoil amendments in future research efforts.

Bjugstad (1979) experienced poor success in planting shrub and tree seedlings directly into spoils in northeast Wyoming, but had good initial survival using containerized plants. An important finding was that plant establishment was enhanced when either gypsum or woodchips were used as a mulch and when sawdust, straw and vermiculite were incorporated into the seedbed (Bjugstad et al. 1981).

It became immediately apparent, during this early state of reclamation technique development, that an essentially permanent alteration of the root zone, using chemical and/or physical means, would be necessary to achieve long-term vegetation success.

In 1979, the Reclamation Research Unit at Montana State University began a research project designed to test state-of-the-art bentonite minesoil reclamation technology. Several sites were selected; however, the Belle Fourche site was the most thoroughly investigated. At Belle Fourche, treatments consisted of surface amendments (deep chiseling and gouging), physical amendments (manure and woodchips), chemical amendments (gypsum, CaCl_2 , and H_2SO_4), topsoiling, irrigation, and a nonamended control plot. Project duration was planned for several years, which would have been sufficient time to evaluate treatment effects in terms of long-term plant performance; the true test of successful reclamation. Unfortunately, funding was discontinued after one sampling season (Dollhopf and Bauman, 1981). This was disappointing to the researchers involved, but it was particularly unfortunate for mine operators and government agencies that were preparing to implement extensive reclamation efforts on orphan spoils.

First year vegetation data suggested that woodchips and topsoil promoted the best germination and growth. Because these treatments provided the most immediate amelioration of the root zone, these results were biased in favor of these treatments. The chemically amended treatments were, in a sense, biased against because the chemicals had not had sufficient time to react in the soil and modify the rooting environment. These first year data were only preliminary but were, unfortunately, the basis for much reclamation in the years that followed.

4.5.2 Recent Bentonite Reclamation Research

Sieg et al. (1983) evaluated canopy cover, standing crop and soil properties on orphan spoils, reclaimed soils (recontoured and topsoiled), newly mined land and native rangeland in southeast Montana. Canopy cover was 32, 12 and 3 percent

on native rangeland, reclaimed spoil, and newly mined or orphan spoils, respectively. Production averaged 428, 231, 91 and 56 kg/ha on native rangeland, reclaimed, newly mined and orphan spoil, respectively.

To a large extent, reclamation and research efforts during the early 1980s focused on the use of wood products (woodchips, sawdust, and wood residue) to amend bentonite minesoils and orphan spoils. Successful plant establishment and growth has generally been achieved through these efforts. Wood residue incorporated into the surface of spoils has increased aboveground biomass and canopy cover of seeded species compared to nonamended control plots (Schuman and Sedbrook 1984, Smith et al. 1985). This occurred as a result of reduced bulk densities, improved soil structure, increased infiltration and plant available water, and reduced electrical conductivity. A lowering of the electrical conductivity resulted from the leaching of salts from the surface soil and/or the dilution of the surface soil by the addition of wood residue.

Smith et al. (1985) reported that 90 Mg/ha of wood residue plus 2.5 kg of nitrogen/Mg of residue yielded the greatest increase in seeded plant density, aboveground production, and canopy cover. Spoils amended at these rates exhibited a mean first year density of 59 seedlings/m², and second year production and canopy cover of 2060 kg/ha and 67 percent, respectively. In contrast, on the nonamended control plot plant density was 14 seedlings/m², production average 80 kg/ha, and canopy cover was only 8 percent. Also investigated on this site were the differential responses of the species that were seeded.

Some species established poorly, irrespective of the treatment (Stipa viridula) or became established to a limited degree and only on specific treatment combinations (Agropyron trachycaulum, Agropyron desertorum, and Agropyron trichophorum) (Smith et al. 1986). Agropyron smithii and Atriplex nuttallii responded positively to increased residue rates, but were unaffected by fertilization. Bromus inermis, Agropyron riparium/dasystachyum, Agropyron intermedium, and Agropyron elongatum had significant but varied interactive responses to the residue and fertilization combinations. Plant community diversity (Shannon-Wiener index) was greatest for treatments that were less than optimal for production.

In the summer of 1985, members of Montana State University's Reclamation Research Unit visited the Belle Fourche site investigated by Dollhopf and Bauman (1981). What was observed was exciting, if somewhat unexpected. In terms of plant growth, the woodchip treatment had continued to perform moderately well, but some of the chemical treatments exhibited remarkable vegetation growth. On these treatments the

minesoil was friable, and in some cases, plant canopy cover and aboveground biomass exceeded that of adjacent native rangeland. Upon witnessing this success, the State of Montana funded MSU to evaluate these test plots. The results of this reevaluation are reported herein.

5.0 EFFECTS OF H_2SO_4 , $CaCl_2$, GYPSUM, MANURE, WOODCHIPS, TOPSOIL, GOUGING, MULCHING AND EMERGENCE IRRIGATION ON MINE SOIL PHYSICO-CHEMISTRY AND VEGETATION DEVELOPMENT

The purpose of this chapter is to present effects of amendments on bentonite mine soil physicochemical characteristics after seven years. Plant performance in these amended test plots is also presented.

5.1 METHODS AND MATERIALS

5.1.1 Site Description

In April, 1980, field plots were established approximately 11 km (7 miles) northwest of Belle Fourche, South Dakota on orphan bentonite spoils (see Figure 1). The surrounding landscape is composed of gently rolling hills and broad flat valleys. The vegetation is dominated by big sagebrush (Artemisia tridentata ssp. wyomingensis) and mixed prairie grasses on relatively deep soils, ponderosa pine (Pinus ponderosa) on rocky hilltops and ridges, and riparian species in localized areas. Native soils were formed from marine shales and are very fine textured, often saline and sodic, and have inherently low fertility. Plant available water is limited due to low rates of infiltration and naturally low precipitation. The climate of Belle Fourche is semi-arid with an average annual precipitation of 41.95 cm, the majority of which is received from April through June (Climatological Data, NOAA records for Belle Fourche, 1951-1986). Although the initial growing season (1980) had less than average precipitation, summer and fall rains were above normal (Figure 3). Above average precipitation was received during 1981, 1982, 1983 and 1984, but less than half the annual average was received in 1985. Precipitation early in 1986 was above normal. Over the study period, annual precipitation averaged 44.10 cm or 2.15 cm above normal. The frost-free period is approximately 150 days.

5.1.2 Experimental Design and Implementation

A nearly level 60 x 80 m area was chisel plowed to a depth of 30 cm. Five x 15 m plots were delineated into a randomized block design consisting of three replications of each treatment (Figure 4).

Gypsum was 69 percent $CaSO_4 \cdot 2H_2O$ while the remaining portion was mostly crushed rock. The $CaCl_2$ was 94 percent pure (Type 2). Both gypsum and $CaCl_2$ were applied by hand in granular form. The H_2SO_4 was applied with plastic sprinkling cans as 36 N H_2SO_4 (94 percent pure). Application rates for these

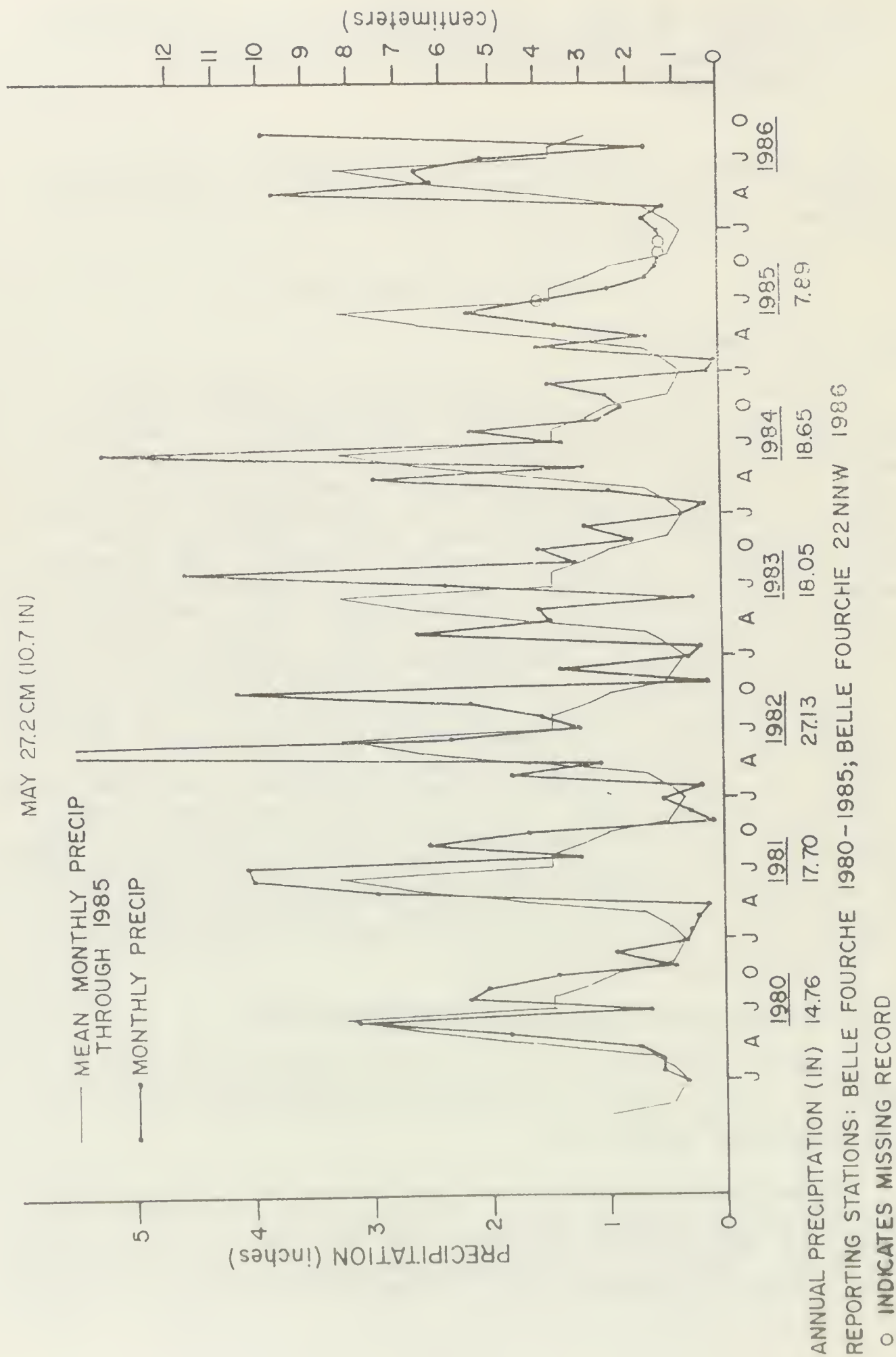
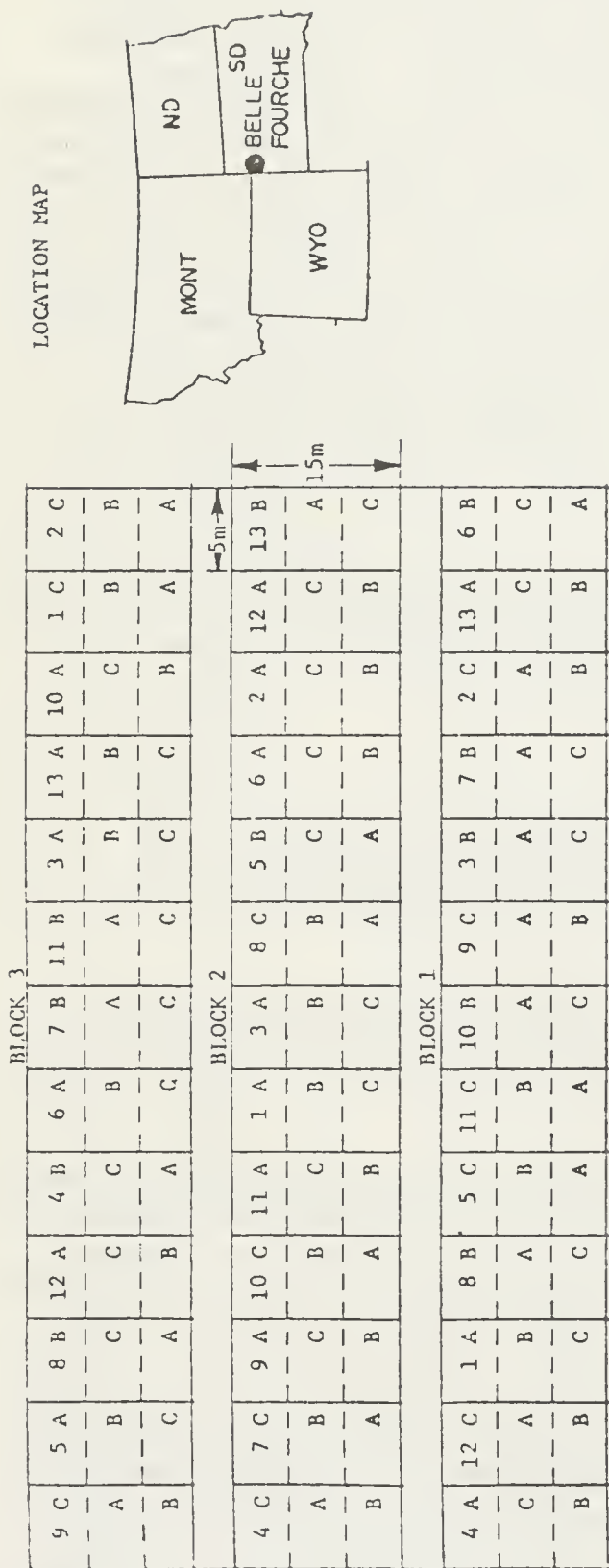


Figure 3. Precipitation data for Belle Fourche, SD.



TREATMENT CODE*

- 1) No straw mulch
 - 2) Control
 - 3) Emergence irrigation
 - 4) Gouge
 - 5) Vertical mulch with manure
 - 6) Manure, 224 mt/ha (100T/A)
 - 7) Manure, 112 mt/ha (50T/A) + H₂SO₄ 20 mt/ha (9T/A)
 - 8) Woodchips, 1660 m³/ha (879 yd³/A)
 - 9) Gypsum, 6.7 mt/ha (3.0T/A) + CaCl₂, 17.2 mt/ha (7.7T/A)

- 10) Gypsum, 6.7 mt/ha (3.0T/A) + H₂SO₄, 12.3 mt/ha (5.5T/A)
 - 11) Gypsum, 6.7 mt/ha (3.0T/A) + H₂SO₄, 12.3 mt/ha (5.5T/A) + irrigation
 - 12) 10.2 cm (4 in.) topsoil
 - 13) 10.2 cm (4 in.) topsoil with irrigation
 - A) No N applied
 - B) N, 67 Kg/ha (60lb/A)
 - C) N, 134 Kg/ha (120lb/A)
- * All treatments except as noted received straw mulch @ 4.5 mt/ha (2.0T/A)

Figure 4. Experimental design implemented in 1980 at Belle Fourche, South Dakota.

chemicals were based on the amount of exchangeable Na^+ present in the minesoil (USDA 1954). The goal was to reduce the ESP to 10. For comparison, chemically equivalent amounts of gypsum + CaCl_2 and gypsum + H_2SO_4 were applied to the respective plots. Cattle manure was obtained from a local feedlot and the woodchips came from a nearby sawmill. Once these amendments were applied to the spoil surface, the entire study area was rototilled to a depth of 12 cm. Topsoil was obtained from adjacent native range. The vertical mulch treatment consisted of 15 cm wide ditches 1.0 m deep and spaced 1.0 m apart that were filled with cattle manure. Irrigation water was pumped from an abandoned bentonite pit and applied to selected treatments at 0.6 cm/day for 20 consecutive days after seeding. Except for treatment number one, all treatments were mulched with 4500 kg ha^{-1} (2 T/A) of straw. Each plot was subdivided into 5 x 5 m plots for testing three nitrogen fertilizer rates (0, 67, 134 kg ha^{-1} ; or 0, 60, 120 pounds per acre).

All plots were broadcast seeded by hand with a diverse mixture of native and introduced species (Table 1). Following seeding, the study area was subjected to a mulch crimper to anchor the straw and provide a firm seedbed.

5.1.3 Plant Sampling Methodology

Emergent plant density was measured in July 1980 by counting seedlings in ten systematically located 0.25 m^2 microplots in each subplot. Plants were separated by life form; grasses, forbs and shrubs.

Aboveground plant production, species specific canopy cover, and root biomass were collected in 1986 to evaluate plant performance on the treatments after seven complete growing seasons.

Production was estimated by hand-harvesting eighteen 50 by 50 cm subplots (frames) per treatment. These subplots were systematically located at regular intervals along a transect that bisected each study plot on the diagonal. All herbaceous vegetation was clipped at ground level and separated in the field into the appropriate life form; perennial grass, annual grass, and forbs (perennial and annual). Shrubs were clipped at ground level and represent an accumulation of six years of growth. Organic litter was also collected. Samples were air-dried to a constant weight and weighed to the nearest tenth gram.

Cover was estimated for each plant species in each treatment using thirty 20 by 50 cm subplots following the polygon method of Daubenmire (1968).

Table 1. Seed mixture and rates, Belle Fourche, SD, April 1980.

<u>Scientific Name</u>	<u>Common Name</u>	<u>Broadcast Seeding Rate: PLS/m²</u>
Agropyron cristatum (L.) Gaertn.	Crested wheatgrass	4.6
Agropyron dasystachyum (+A.D. riparium) (Hook.) Scribn.	Thickspike wheatgrass	12.0
Agropyron elongatum (Host) Beauv.	Tall wheatgrass	12.0
Agropyron smithii Rydb.	Western wheatgrass	10.0
Agropyron trachycaulum (Link) Malte ex H.G. Lewis	Slender wheatgrass	7.0
Bouteloua curtipendula (Michx.) Torr.	Sideoats grama	7.0
Sporobolus airoides (Torr.) Torr.	Alkali sacaton	0.6
Achillea millefolium L.	Western yarrow	0.6
Helianthus spp.	Sunflower	0.6
Kochia prostrata (L.) Schrader	Prostrate kochia	0.5
Linum lewisii Jeps.	Lewis flax	1.0
Ratibada columifera Raf.	Prairie coneflower	5.0
Astragalus cicer L.	Cicer milkvitch	8.0
Mililotus officinalis (L.) Lam.	Yellow sweetclover	4.0
Atriplex canescens (Pursh) Nutt.	Fourwing saltbush	1.2
Atriplex gardneri (Moq.) D. Dietz	Gardner saltbush	1.2
Sarcobatus vermiculatus	Greasewood	0.6
		76.6

Plant root material was collected using a Giddings soil sampler with a 6.5 cm diameter core barrel. Two, 45 cm cores were extracted from each plot and consolidated. In the laboratory, these cores were air-dried. Root biomass was determined by a combination dry sieve and decant method. Each core sample was weighed then mortared and pestled to break-up the core and the larger roots collected. The sample was passed through a series of sieves consisting of a 2.0, 1.0, 0.42 and a 0.25 mm sieve. Any material not passing the 0.25 mm sieve was decanted with water. Floating organic matter was col-

lected by pouring it through a 0.42 mm sieve; this was similar to the method outlined by Bohn (1979). Organic material collected through the decanting procedure was air-dried to a constant weight. After drying, organic material other than roots were manually separated and discarded with the help of a slanted, vibrating cleaning table. Recorded root weights were converted to root biomass per 1000 grams of spoil.

5.1.4 Minesoil Sampling and Analysis Methods

Prior to establishment of test plots, two composite samples were collected from the planned research area in order to characterize the physicochemical characteristics of the mine-soil. These samples were analyzed for parameters listed in Table 2 in accordance with the referenced procedure. In addition to those parameters listed in Table 2, the following anions were determined.

- HCO₃, CO₃
Extract from water saturated soil paste followed by electrometric titration. 1954 USDA Handbook 60, Method 12, p. 98.
- SO₄
Extract from water saturated soil paste followed by precipitation of BaSO₄ from solution. 1954 USDA Handbook 60, Method 14a, p. 99.
- Cl
Extract from water saturated soil paste. 1954 USDA Handbook 60, Method 13, p. 98.

Prior to treatment application in 1980, composite (3) minesoil samples were collected from each plot in increments of 0-30, 30-60, 60-90, 90-120 and 120-150 cm. Six years later (1986), three composites from each plot were sampled in increments of 0-5, 5-10, 10-20, 20-38, 38-76 and 76-152 cm. Minesoil samples were air-dried and disaggregated. That portion passing a 2.0 mm sieve was analyzed for electrical conductivity (EC), pH and sodium absorption ratio (SAR) according to procedures specified in Table 2.

Infiltration rates were measured on all test plots using an infiltrometer similar to the unit developed by Chow and Harbaugh (1965), and built from construction plans presented in Meeuwig (1971). A runoff collection frame of 48 x 48 cm was used to catch and funnel runoff into a container. Simulated rainfall was applied at a constant rate of 12 cm/hr (4.72 in/hr) for 30 minutes (Meeuwig 1971). Runoff was measured in milliliters at five minute intervals. When necessary, plastic skirting was placed around the infiltro-

Table 2. Minesoil physicochemical analysis procedures.

Sodium Absorption Ration (SAR)

This determination was made on the extract from a water saturated soil paste. Agriculture Handbook No. 60, USDA, 1954, p. 84-88.

$$SAR = \text{meq/L Na} / ((\text{meq/L Ca} + \text{meq/L Mg})/2)^{1/2}$$

Calcium, Magnesium, Sodium (water extract)

Determination by Atomic Absorption Spectroscopy using saturation extract. Agriculture Handbook No. 60, USDA, 1954, p. 84-88.

Calcium, Magnesium, Sodium, Potassium (NH₄OAc extract)

Agriculture Handbook No. 60, USDA, 1954, Method 18, p. 100-101.

Conductance

This determination was made on the extract from a water saturated soil paste. Agriculture Handbook No. 60, USDA, 1954, p. 89.

pH

This determination was made on a water saturated soil paste. Agriculture Handbook No. 60, USDA, 1954, p. 102.

Saturation Percentage

Grams H₂O/grams soil to attain saturation times 100. Agriculture Handbook No. 60, USDA, 1954, Method 2 and 3a.

Particle Size Analysis (hydrometer)

A.S.A. Agronomy Monograph No. 9, 1965. Methods of Soil Analysis. Part 1, Method 43-5, p. 562-566. Textural triangle was used for texture class identification, Soil Survey Manual, 1951, USDA, p. 209.

Nitrate

Phenoldisulfonic acid method. A.S.A. Agronomy Monograph No. 9, 1965. Methods of Soil Analysis, Part 2, p. 1212-1214.

Boron

Hot water extraction. A.S.A. Agronomy Monograph No. 9, 1965. Methods of Soil Analysis, Part 2, Method 75-4, p. 1062-1063.

Copper, Cadmium, Iron, Lead, Manganese, Zinc and Nickel

Atomic absorption analysis of DTPA extract. Soil Science Soc. of American Proceeding, Vol. 35, No. 4, 1971, p. 600-602.

Molybdenum

Acid ammonium oxalate extraction. A.S.A. Agronomy Monograph No. 9, 1965. Methods of Soil Analysis, Part 2, p. 1054-1057.

Selenium

Determination by the gaseous hydride method after hot water extraction. The Se is reduced from +6 oxidation state to +4 oxidation state by addition of NaBH₄ solution to produce H and convert Se to SeH₂. The gaseous SeH₂ is swept into N flame of AA for determination. EPA, Methods for Chemical Analysis of Water and Waste, 1974. Extraction procedure also presented in A.S.A. Monograph No. 9, 1965. Methods of Soil Analysis, Part 2, 80-3.2.2, p. 1122.

Mercury

Acid extraction determined by cold vapor generation and atomic absorption spectroscopy. Anal. Chem. Vol. 40, No. 114 (1968). Also Manual of Methods for Chemical Analysis of Water and Wastes, EPA, 1974, p. 137, Procedure 8.1.

Phosphorus

Colorimetric determination of NaHCO₃ extraction. A.S.A. Monograph No. 9, 1965. Methods of Soil Analysis, Part 2, Method 73-4.4, p. 1044-1047.

Exchangeable Sodium Percentage (ESP)

Exchangeable Na determined by NH₄OAc extraction and subtraction of the H₂O soluble fraction. Cation exchange capacity (CEC) determined by NaOAc saturation and HN₄OAc extraction. Agriculture Handbook No. 60, USDA, 1954, Methods 18 and 19, p. 100-101.

$$ESP = ((\text{meq}/100\text{g Na}) / (\text{meq}/100\text{g CEC})) \times 100$$

meter to prevent the effects of wind. Total runoff volumes were converted to percent infiltration and a mean infiltration value was calculated for each treatment.

Individual infiltration plots were located by establishing a transect line diagonally across each test plot and locating the infiltration test 7.5 meters from the plot corner. The runoff collection frame was tapped into the ground and sealed along the outside with clay. Vegetation was clipped to ground level and litter removed.

Modulus of rupture was determined according to Method 43 presented by USDA (1954). Saturated hydraulic conductivity was determined on minesoil material according to Method 346 presented by the USDA (1954). Hydraulic conductivity values represent equilibrium flow rates, that is, when K stabilized to a near constant value which required several days.

Clay mineral analysis was performed using the x-ray diffraction technique of Whittig (1965) and semiquantitative analysis (Klages and Hopper 1982) was used to estimate relative proportions of the clay minerals.

5.2 RESULTS

5.2.1 Minesoil Physicochemical Characteristics

Field observations indicated that gypsum crystals ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) were abundant in minesoil material. This minesoil required a source of calcium for reclamation of the dispersed physical condition, however, the form of gypsum present was apparently very insoluble. No visible "fizz" reaction resulted when a 10% HCl solution was applied to this minesoil. Therefore, alkaline earth carbonates were absent or present at very low levels. This minesoil was dominated by shale fragments mixed with bentonite wastes.

Plant growth on these minesoils was limited by the very sodic (SAR 33-37) and clayey (60-68%) nature of these materials (Table 3). These sodic and clayey conditions dominated by smectite mineralogy (Table 4) resulted in a very slow saturated hydraulic conductivity (.003 cm/hr). Surface crusts formed immediately after being wetted and dried. Crust strength was very high (> 5.7 bars) and could prevent seedling emergence or cause plant stem breakage.

The salinity level was moderately high (7.7 mmhos/cm) and trace element levels were not limiting to plant growth (Table 3). The dominant anion was sulfate. The minesoil pH was good (7.6) for plant growth. Nitrate levels were very low and phosphorus levels were moderate.

Table 3. Physicochemical characteristics of two composite minesoil samples used for this investigation located near Belle Fourche, SD.

Sample	Depth (cm)	pH	EC* mmhos/cm	SAR*	ESP*	Water Extract			NH ₄ OAc Extract			CEC*
						Na	Ca	Mg	Na	Ca	Mg	
						meq/L			meq/100g			
1	0-15	7.6	7.7	33.4	46.5	112.0	11.8	10.8	28.0	8.4	10.9	39.6
2	0-15	7.7	7.7	37.3	6.7	102.2	10.2	6.9	13.5	9.3	10.2	37.4

NO ₃	P	SO ₄	HCO ₃	CO ₃	Cl	Pb	parts per million										Mo	B	Sat. %	Sand Silt Clay			Texture
							Ni	Zn	Fe	Mn	Cu	Cd	Hg	Se	%								
5.7	15.6	6747	44.8	0.0	95.9	1.6	5.0	8.8	84.8	13.7	6.0	0.40	0.004	0.011	0.34	0.0	86	8.9	31.2	59.9	Clay		
3.4	17.4	6203	44.8	0.0	86.0	2.0	5.1	11.0	43.0	25.8	5.6	0.51	0.004	0.009	0.30	0.0	101	2.3	30.0	67.7	Clay		

* EC = Electrical Conductivity; SAR = Sodium Adsorption Ratio; ESP = Exchangeable Sodium Percentage; CEC = Cation Exchange Capacity

Table 4. Minesoil modulus of rupture, hydraulic conductivity and clay mineralogy.

Analysis	Composite Minesoil Sample 1	
Modulus of Rupture	> 5.7 bars	
Saturated Hydraulic Conductivity	0.003 cm/hour	
Clay Mineralogy (approximate % of each)		
• Smectite	63	
• Illite	17	
• Kaolinite	9	
• Quartz	11	

5.2.2 Effects of Chemical and Physical Amendments on Bentonite Minesoils

5.2.2.1 Sodicity

Prior to amendment application in 1980, all test plots had sodic conditions (Table 5) and the mean SAR for all plots and depths was 31.9 ± 6.1 . SAR values greater than 15 are generally considered to negatively impact agronomic crops, although some plants, particularly adapted native species, can tolerate SAR values in excess of 15.

Except for differences between depths in one treatment, there were no significant differences between treatments or depths in 1980, indicating uniform sodicity across the study area prior to the application of amendments (Table 5). The SAR differences between depths in the gypsum + CaCl_2 treatment resulted from a high value (47.7) near the spoil surface and a comparatively low value (16.8) in the lowest depth interval. This trend was notable and was therefore considered in the evaluation of data from 1986. A comparison of data from 1980 and 1986 indicated sodicity did not significantly change in the minesoil 0-38 cm depth in the unamended control during the six year study period (Table 6). Spoil SAR was also not significantly affected by emergence irrigation, gouging, manure by itself and woodchips. Significant reductions in SAR occurred in the surface 5 cm as a result of no straw mulch application and vertical mulching with manure.

Treatments demonstrating the greatest reduction in SAR near the surface and at depth were those amended with H_2SO_4 in combination with either manure or gypsum (Table 6, Figure 5). Significant reductions in spoil SAR down to the 20 cm depth occurred for the manure + H_2SO_4 , the gypsum + H_2SO_4 and the gypsum + H_2SO_4 + irrigation treatments. Substantial reductions in the mean SAR were also noted in the 0-5 and 5-10 cm minesoil depths where manure was used alone, however, these were not statistically significant. The use of gypsum with CaCl_2 resulted in a significant reduction in SAR at the surface (0-5 cm), and notable reductions in mean SAR down to the 38 cm minesoil depth.

In 1980, 10 cm of topsoil (SAR 1) was placed over sodic spoils. Six years later, the entire topsoil zone was sodic (SAR 28.0-32.9) and not suitable for plant growth (Table 6).

Six years after amendment application, three amendment treatments were significantly better than all others in reducing minesoil sodicity (Table 6). They were:

Table 5. Mean¹ 1980 SAR values, Belle Fourche, SD.²

Depth (cm)	Treatment												
	no straw	control	irrgtn	gouge	manure		manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum			
					vertical mulch	only				gypsum +H ₂ SO ₄	+irrgtn	topsoil only	topsoil +irrgtn
0-30	38.6	33.8	33.9	34.8	32.5	36.9	34.8	38.1	47.7 a	38.4	33.5	35.8	35.8
30-60	32.7	31.1	33.1	36.6	31.0	30.7	30.8	33.4	28.0 ab	31.3	34.8	30.2	31.6
60-90	29.0	31.8	29.4	32.6	32.1	33.9	29.8	28.4	22.0 ab	30.8	33.2	27.9	30.8
90-120	31.3	45.9	30.0	27.3	33.7	37.3	26.0	25.6	27.6 ab	27.4	32.7	39.4	35.0
120-150	27.1	41.2	34.7	26.7	36.6	32.7	26.3	25.8	16.8 b	30.8	27.8	28.3	38.7

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly (P<.05) different if associated with a different letter.

Table 6. Mean¹ SAR values compared between years, Belle Fourche, SD².

Year	Depth (cm)	Treatment												
		no straw	control	irrigtn	gouge	manure vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +H ₂ SO ₄ irrigtn	topsoil only	topsoil +irrigtn
80	0-5	38.7 A	33.8	33.9	34.8	32.5 A	36.9	34.8 A	38.1	47.7 A	38.4 A	33.5 A	1.0 B	1.0 B
86		31.6 B	38.7	44.1	37.7	28.1 B	20.1	8.8 B	34.3	9.2 B	7.3 B	10.1 B	26.3 A	28.0 A
80	5-10	38.7	33.8	33.9	34.8	32.5	36.9	34.8 A	38.1	47.7	38.4 A	33.5 A	1.0 B	1.0 B
86		32.2	33.4	35.0	37.2	33.7	26.2	14.9 B	38.7	10.2	16.4 B	16.2 B	27.2 A	32.9 A
80	10-20	38.7	33.8	33.9	34.8	32.5	36.9	34.8 A	38.1	47.7	38.4 A	33.5 A	35.8	35.8
86		32.4	35.0	28.2	30.9	34.9	32.5	20.8 B	33.9	18.7	19.0 B	16.9 B	29.0	36.2
80	20-38	38.7	33.8	33.9	34.8	32.5	36.9	34.8	38.1	47.7	38.4	33.5	35.8	35.8
86		30.1	35.0	28.6	28.2	30.8	31.7	27.7	31.6	26.6	26.1	27.8	33.8	35.6

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Mean values are significantly (P<.05) different if followed by a different letter.

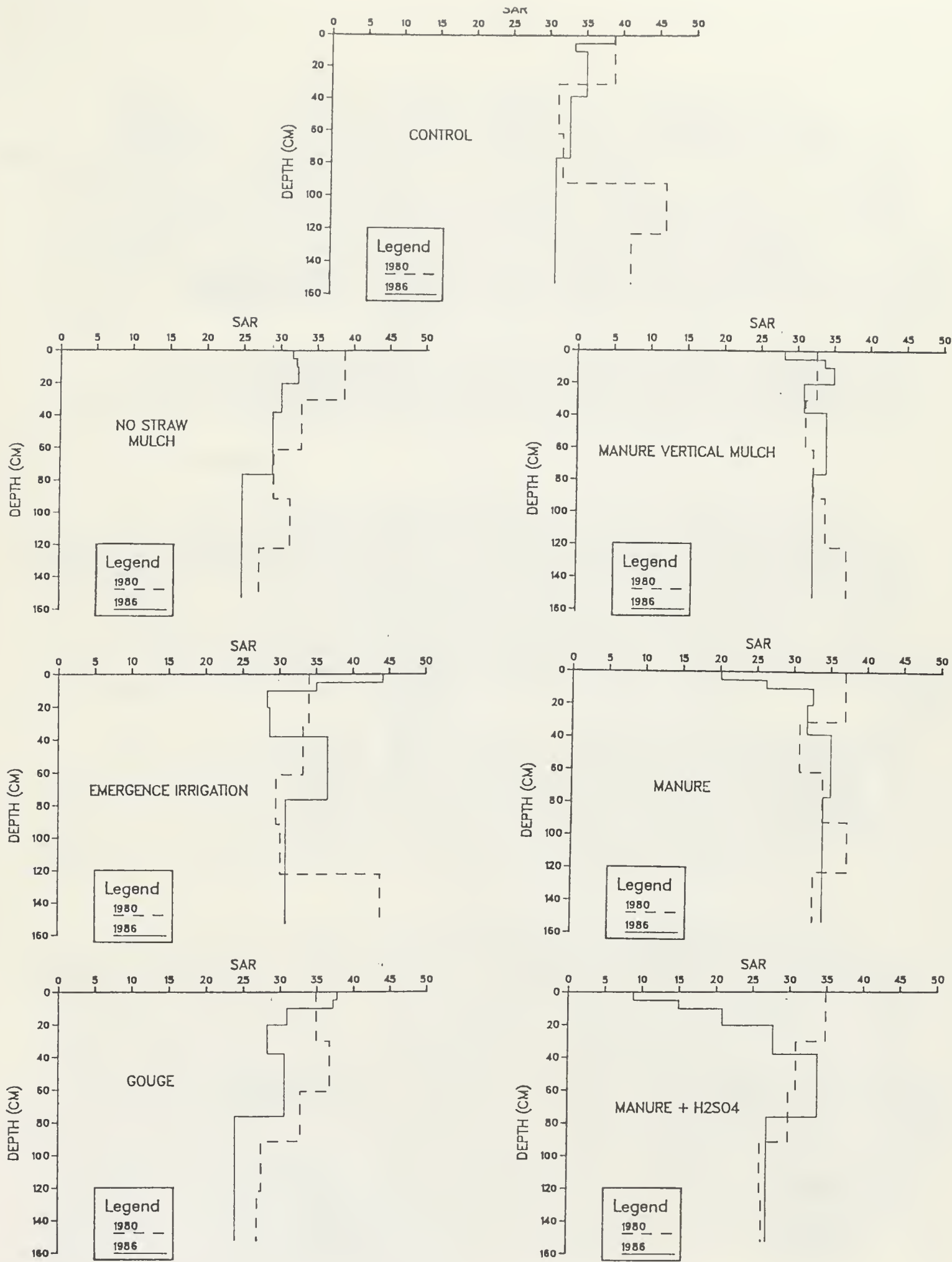


Figure 5. Spoil profile SAR for amendment treatments in 1980 and 1986, Belle Fourche, SD.

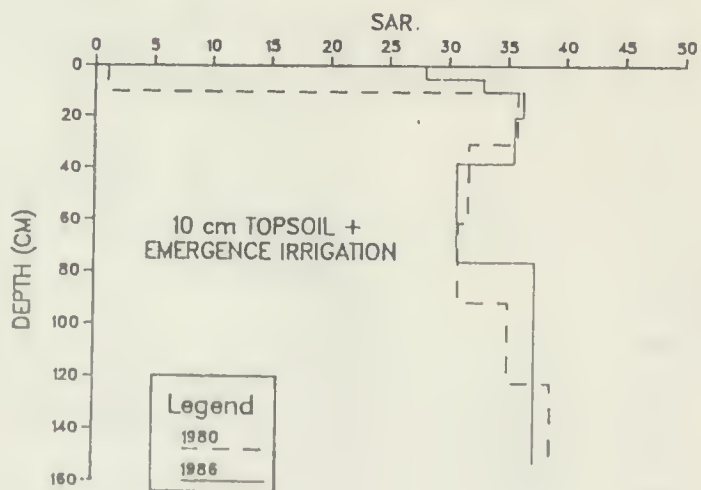
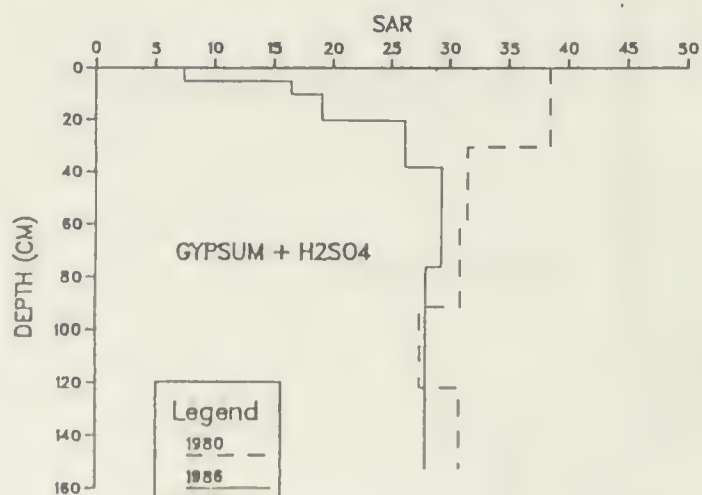
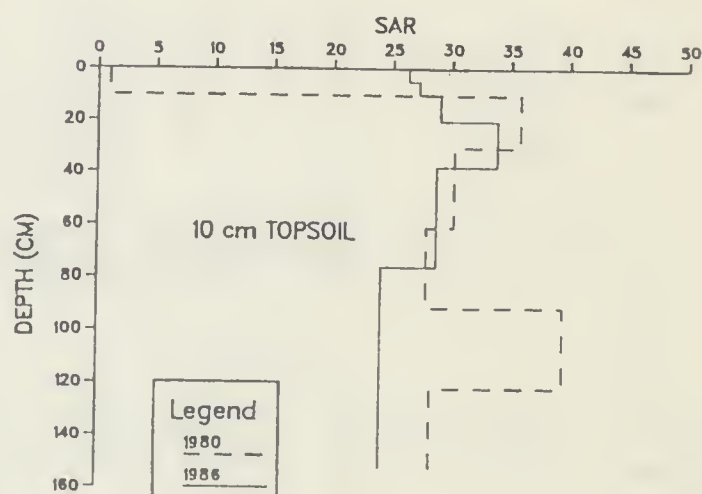
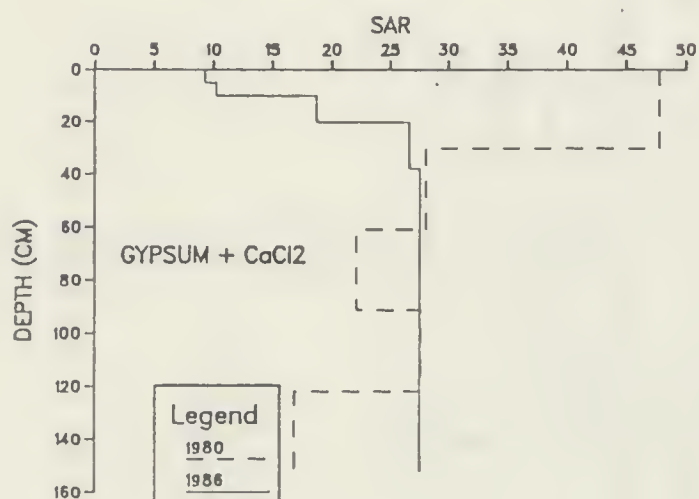
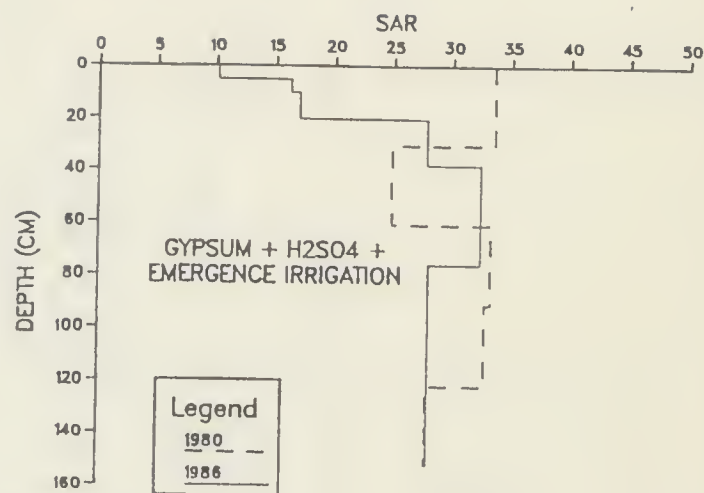
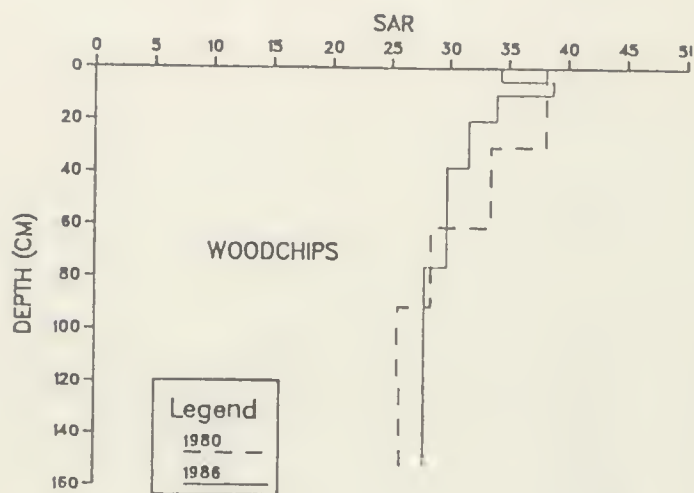


Figure 5. Continued.

- Manure, 112 mt/ha(50 T/A) + H₂SO₄, 20 mt/ha(9 T/A)
- Gypsum, 6.7 mt/ha(3 T/A) + H₂SO₄, 12.3 mt/ha(5.5 T/A)
- Gypsum, 6.7 mt/ha(3 T/A) + CaCl₂, 17.2 mt/ha(7.7 T/A)

These three treatments were not significantly different from each other pertaining to their ability to reduce SAR in bentonite mine soils (Table 7). In general, these amendments reduced SAR effectively to the 20 cm depth, while SAR at greater depths was not significantly changed compared to the control. These changes in SAR with depth are clearly shown in Figure 5.

An understanding of the mechanisms and pathways by which these chemical amendments reclaimed bentonite mine soils is presented in the discussion (Section 5.3). Before implementing or rejecting these results for field project work, the reader should understand the principles in the discussion.

5.2.2.2 Salinity

Prior to amendment application in 1980, all test plot mine soils had saline conditions (Table 8), and the mean electrical conductivity (EC) was 7.4 ± 0.8 mmhos/cm. This level of mine soil salinity is considered moderately high, but should not seriously limit establishment and production of most grasses, forbs and shrubs planted at this site. The concern was that the addition of inorganic and manure amendments may increase the salt content of the mine soil to a level that is unacceptable for plant growth.

Prior to amendment application, the mine soil material was uniform in salt content as indicated by the lack of significant differences in EC values between treatments or depths (Table 8). The gouged treatment, however, showed EC differences with depth, but since no pattern was evident, the differences were attributed to either material variation or sampling error.

Between 1980 and 1986, no statistically significant changes in EC occurred at any depth in the control, no straw mulch, manure only and woodchip treatments (Table 9). The woodchips treatment had a decrease in mean EC in the 0-10 cm depth probably because the woodchips either diluted the mine soil chemistry and/or increased infiltration, although these differences were not statistically significant. Likewise, the manure only treatment showed apparent reductions in mean EC in each increment down to 20 cm. The gouge and manure vertical mulch treatments had significant increases in EC at specific depths. It is difficult to explain the increase in EC for the gouge treatment, but salts contained in the manure could have resulted in the higher EC levels measured in 1986. During the six year period, significant decreases in mine soil EC near the surface occurred with the following treatments (Table 9).

Table 7. Mean¹ 1986 SAR values, Belle Fourche, SD².

Depth (cm)	Treatment												
	no straw	control	irrgtn	gouge	manure vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +H ₂ SO ₄ +irrgtn	topsoil only	topsoil +irrgtn
0-5	31.6 BC	38.6 AB	44.1 A	37.7 ABC	28.1 BCD	20.1 D	8.7 E	34.3 ABC	9.2 E	7.33 E	10.0 E	26.3 DC	27.9 BCD
5-10	32.1 A	33.3 A	35.0 A	37.1 A	33.6 A	26.2 AB	14.8 BC	38.7 A	10.1 C	16.4 BC	16.1 BC	27.2 AB	32.8 A
10-20	32.3 AB	34.9 A	28.2 ABC	30.8 ABC	34.9 A	32.5 AB	20.7 ABC	33.9 AB	18.6 BC	19.0 BC	16.9 C	29.0 ABC	36.2 A
20-38	30.1	35.0	28.6 b	28.1	30.8	31.7 a	27.7 ab	31.5	26.6 a	26.1 a	27.8 a	33.8 a	35.5
38-76	28.9	32.7	36.5 ab	30.4	33.8	35.0 a	33.7 a	29.7	27.5 a	29.2 a	32.3 a	28.7 ab	30.6
76-152	24.8	30.8	30.7 b	23.7	32.0	34.0 a	26.9 ab	27.8	27.5 a	27.9 a	27.9 a	24.0 b	37.3

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly (P<.05) different if associated with a different letter.

Table 8. Mean¹ 1980 EC (mmhos/cm), Belle Fourche, SD².

Depth (cm)	Treatment													
	no straw	control	irrgtn	gouge	manure			manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄ +irrgtn	gypsum +H ₂ SO ₄ +irrgtn	topsoil only	topsoil +irrgtn
					vertical	mulch	only							
0-30	6.8	7.5	8.3	7.4	ab	6.6	7.4	6.9	7.8	7.2	6.8	7.2	6.0	7.2
30-60	7.4	7.5	8.1	6.4	b	7.6	7.2	8.2	7.4	7.8	7.0	7.8	7.3	7.8
60-90	7.6	6.2	8.3	7.4	ab	7.7	7.8	8.1	7.5	6.9	7.7	8.7	7.1	6.9
90-120	7.6	5.9	8.8	9.4	a	7.4	6.4	8.2	8.1	7.2	8.4	6.6	7.3	7.0
120-150	7.6	4.7	8.9	8.7	a	7.2	6.4	8.2	7.4	5.2	7.5	7.7	6.7	7.4

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly (P<.05) different if associated with a different letter.

Table 9. Mean¹ EC (mmhos/cm) values compared between years, Belle Fourche, SD².

Year	Depth (cm)	Treatment													
		no straw	control	irrigtn	gouge	manure		manure +H ₂ SO ₄	woodchips	gypsum		gypsum +H ₂ SO ₄		topsoil only	topsoil +irrigtn
						vertical mulch	manure only			+CaCl ₂	+H ₂ SO ₄	+H ₂ SO ₄	irrigtn		
80 86	0-5	6.89 8.98	7.53 6.55	8.38 8.89	7.46 7.18	6.65 8.28	7.47 3.03	6.96 A 2.68 B	7.81 3.22	7.22 A 1.56 B	6.88 A 1.63 B	7.20 A 1.31 B	1.00 B 3.88 A	1.00 B 4.00 A	
80 86	5-10	6.89 9.96	7.53 8.24	8.38 10.80	7.46 10.21	6.65 B 11.52 A	7.47 3.15	6.96 3.33	7.81 3.26	7.22 3.55	6.88 A 2.83 B	7.20 2.79	1.00 B 7.02 A	1.00 B 6.45 A	
80 86	10-20	6.89 8.30	7.53 9.32	8.38 10.33	7.46 10.05	6.65 10.48	7.47 4.19	6.96 4.68	7.81 7	7.22 7.79	6.88 5.90	7.20 5.83	6.07 8.21	7.25 10.84	
80 86	20-38	6.89 10.33	7.53 13.93	8.38 10.06	7.46 B 10.69 A	6.65 11.18	7.47 9.05	6.96 8.54	7.81 8.65	7.22 8.20	6.88 10.15	7.20 11.14	6.07 B 14.36 A	7.25 10.84	

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Mean values are significantly different (P<.05) if followed by a different letter.

- Manure, 112 mt/ha(50 T/A) + H₂SO₄, 20 mt/ha(9 T/A)
- Gypsum, 6.7 mt/ha(3 T/A) + H₂SO₄, 12.3 mt/ha(5.5 T/A)
- Gypsum, 6.7 mt/ha(3 T/A) + CaCl₂, 17.2 mt/ha(7.7 T/A)

Prior to amendment application in 1980, the 0-5 cm depth in these plots had a mean EC of 7.0 mmhos/cm, and six years after treatment, these plots had a mean EC of 2.0 mmhos/cm. Apparently, salts were leached deeper into the minesoil profile.

Topsoil applied in 1980 was not saline (EC 1.0 mmhos/cm), but was saline in 1986 (3.8 to 7.0 mmhos/cm). Salts from the spoil apparently migrated upward and salinized the topsoil. This result is consistent with the sodication of this same topsoil material discussed earlier. It is likely that sodium was the dominate cation in topsoil that produced the elevated EC level.

In 1986, minesoils treated with manure, manure with H₂SO₄, woodchips, gypsum with CaCl₂, and gypsum with H₂SO₄ all significantly decreased EC to the 10 cm depth compared to the control (Table 10). Gypsum combined with CaCl₂ significantly reduced EC to the 38 cm depth, although the 10-38 cm minesoil depth was still moderately saline (7.7-8.2 mmhos/cm). Other treatments mentioned above significantly reduced EC to the 20 cm depth, but again, the 10-20 cm depth was still moderately saline (4.1-7.1 mmhos/cm).

It can be surmised from Figure 6 that after six years, inorganic amendments (meaning gypsum, H₂SO₄ and CaCl₂) did not increase minesoil salinity in the shallow root zone (0-20 cm). Certainly the salt level of this zone was increased in 1980 when the amendments were applied, but excess native sodium was apparently leached into the 20-150 cm zone resulting in a net loss of salts from the shallow root zone.

5.2.2.3 Acidity

Prior to amendment application in 1980, there were no significant differences in the 0-30 cm depth for pH (Table 11). Mean values for plots ranged from 6.9 to 7.6. Statistically significant variation was present between plot areas in the 30-60 cm depth, but the range in pH values was only 6.5 to 8.2. In general, the minesoil material had a relatively uniform pH between plots and across vertical increments to the 150 cm depth.

Between 1980 and 1986, the pH was significantly changed in the 0-5 and/or 5-10 cm depths for minesoils treated with manure, manure with H₂SO₄, gypsum with CaCl₂, gypsum with H₂SO₄, and topsoil (Table 12). Sulfuric acid was a major concern. Plot pH values for these treatments showed - significant decreases between 1980 (7.1-7.3) and 1986

Table 10. Mean¹ 1986 EC (mmhos/cm) values, Belle Fourche, SD².

Depth (cm)	Treatment										
	no straw			manure				gypsum			
	control	irrgtn	gouge	vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +irrgtn	topsoil +irrgtn
0-5	8.9 A	6.5 ABC	8.8 A	7.1 AB	8.2 A	3.0 BCD	2.6 CD	3.2 BCD	1.5 D	1.6 D	3.8 BCD
5-10	9.6 AB	8.2 AB	10.8 AB	10.2 AB	11.5 A	3.1 C	3.3 C	3.2 C	3.5 C	2.8 C	7.0 ABC
10-20	8.3	9.3 ab	10.3	10.0	10.4	4.1 C	4.6 bc	7.1 c	7.7 b	5.9 bc	8.2 bc
20-38	10.3	13.9 a	10.0	10.6	11.1	9.0 b	8.5 ab	8.6 bc	8.2 b	10.1 ab	14.3 a
38-76	10.6	10.8 ab	13.0	10.1	11.1	12.3 a	12.0 a	11.2 ab	11.8 a	12.7 a	10.9 b
76-152	10.7	8.1 ab	11.7	9.9	11.1	9.3 b	10.9 a	12.4 a	13.6 a	12.3 a	9.7 bc

1 Mean of three replications.
2 Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly (P<.05) different if associated with a different letter.

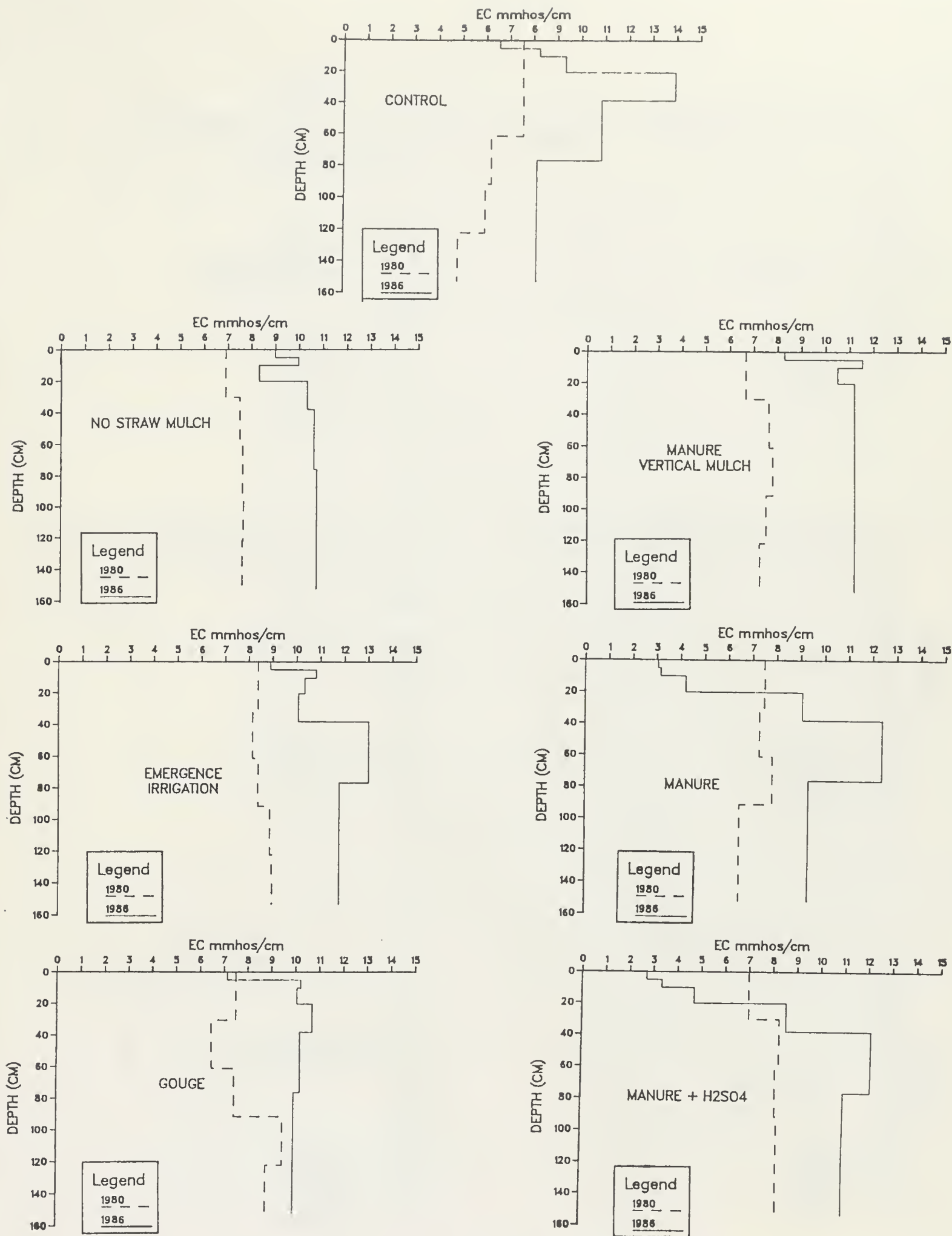


Figure 6. Spoil profile EC (mmhos/cm) for amendment treatments in 1980 and 1986, Belle Fourche, SD.

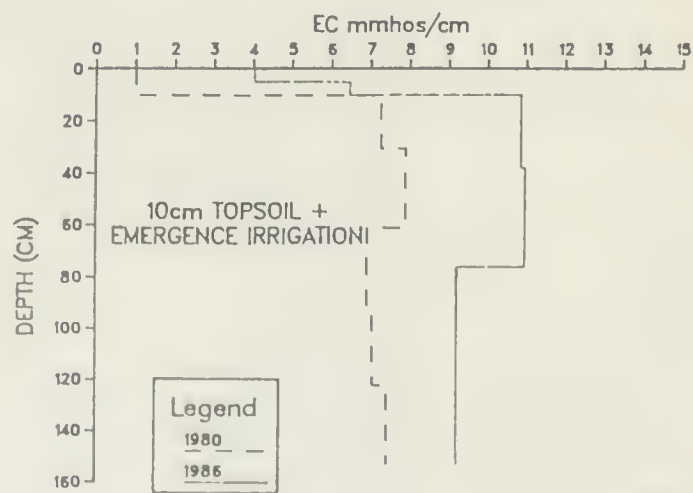
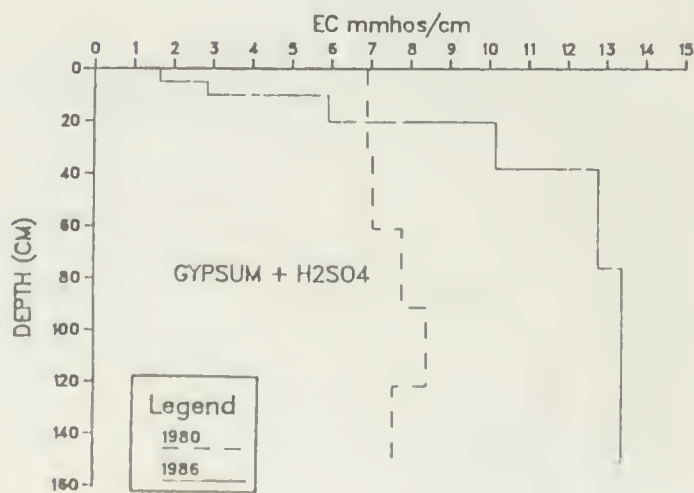
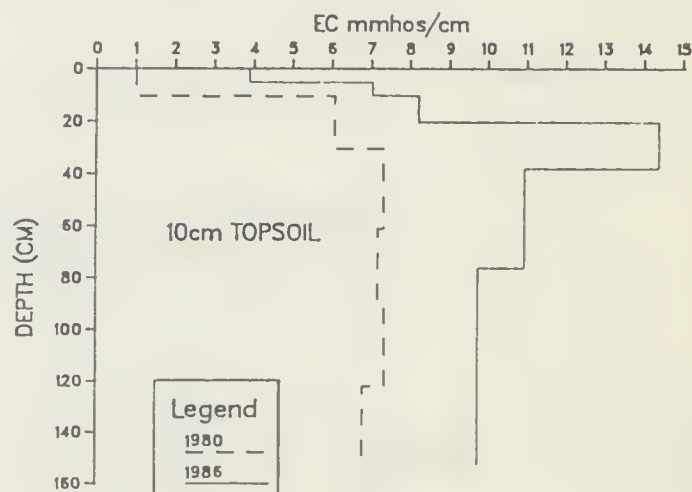
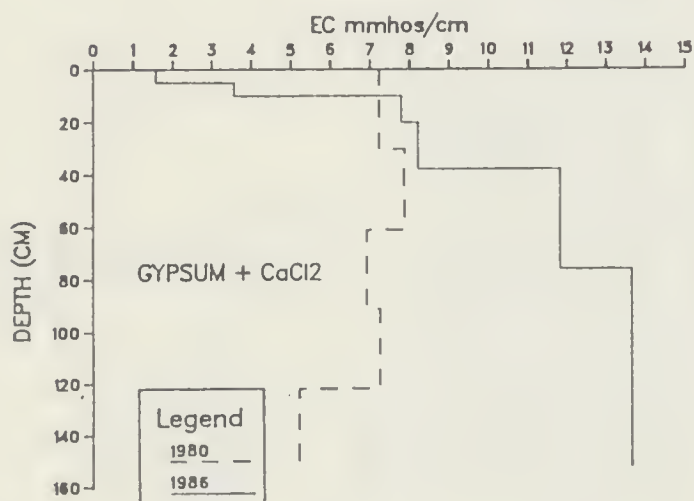
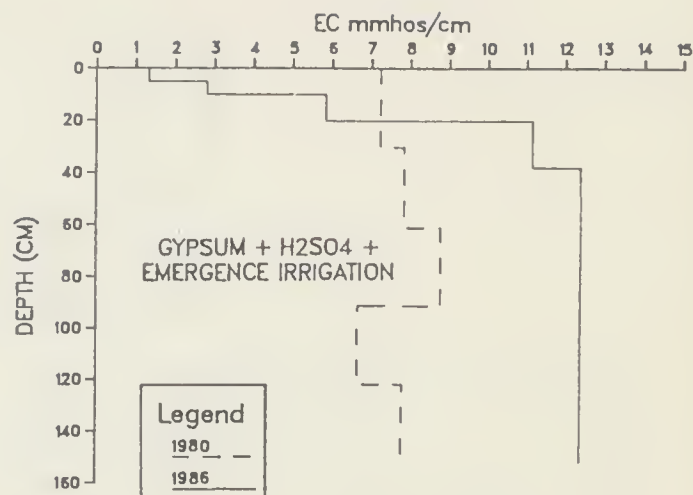
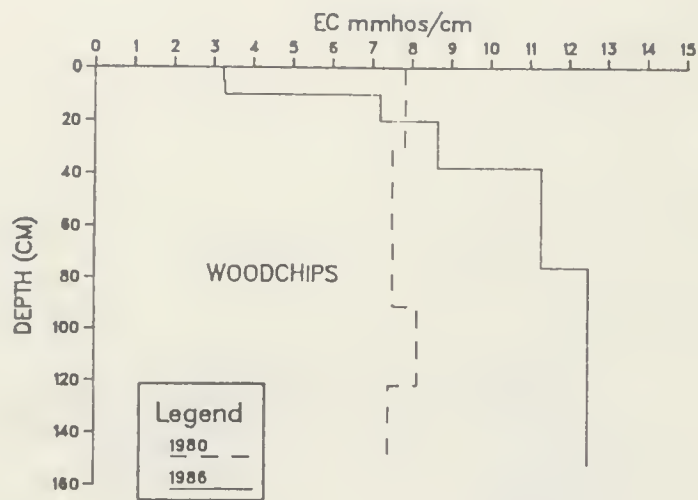


Figure 6. Continued.

Table 11. Mean¹ 1980 pH values, Belle Fourche, SD².

Depth (cm)	Treatment												
	no straw	control	irrigtn	gouge	manure vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +H ₂ SO ₄ +irrigtn	topsoil only	topsoil +irrigtn
0-30	6.9	7.4	7.5	7.3	7.6	7.1	7.2	7.3	6.9	7.1	7.1	7.4	7.5
30-60	7.2	7.2	7.2	6.9	7.6	7.8	7.4	7.2	6.5	7.0	7.0	8.2	7.7
	AB	AB	AB	AB	AB	AB	AB	AB	B	AB	AB	A	AB
60-90	7.2	7.7	7.1	6.9	7.3	7.3	6.8	7.2	6.8	6.8	7.3	6.6	7.9
90-120	7.3	8.0	6.7	7.2	7.5	8.1	6.9	7.4	6.9	6.9	7.6	7.0	7.3
120-150	7.6	8.2	6.7	7.6	7.2	8.0	7.3	7.4	5.1	7.4	7.2	7.7	7.0

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly ($P \leq .05$) different if associated with a different letter.

(4.3-5.4). In general, when soil pH values are below 5.5, plant productivity may decrease due to unavailability of essential nutrients. Trace elements also become more soluble at low pH, creating potential phytotoxic problems.

Minesoil treatment with manure increased the pH approximately 1.5 units to a level greater than 8.5 (Table 12). This result is undesirable since this high pH may decrease the availability of essential nutrients. The gypsum with CaCl_2 treatment increased minesoil pH approximately one unit, but these levels in 1986 were acceptable. As the topsoil became sodic from 1980 to 1986, its pH increased, often to undesirable levels exceeding 8.5.

Between 1980 and 1986, significant changes in minesoil pH did not occur below the 10 cm depth in any treatments (Table 12). Effects of treatments on pH near the surface and to the 150 cm depth are clearly demonstrated in Figure 7.

In 1986, only those plots that received H_2SO_4 had pH levels significantly lower than the control (Table 13). This was the result for both the 0-5 and 5-10 cm minesoil depths. At depths greater than 10 cm, the pH was not significantly different in any treatments compared to the control. The significantly elevated pH in the manure, gypsum with CaCl_2 , and topsoil treated minesoils was also present in either the 0-5 or 5-10 cm depths.

5.2.2.4 Infiltration

Simulated rainfall at a rate of 12 cm/hr over 30 minutes was used to mimic the short duration-high intensity thunder-showers common to the area. Given the 6 cm of water applied during the 30 minute test, minesoils treated with manure, woodchips and gypsum plus CaCl_2 infiltrated significantly more water compared to the control (Table 14). All other treatments either were not significantly different compared to the control or infiltrated significantly less than the control.

These sodic minesoils typically allowed near normal infiltration for 5 to 10 minutes, but exhibited dramatic infiltration rate reductions after 10 minutes due to soil pore blockage from clay dispersion. After 30 minutes, only the following minesoil treatments had a significantly greater infiltration rate compared to the control (Table 15).

- Manure, 224 mt/ha (100 T/A)
- Woodchips, 1660 m³/ha (879 yd³/A)
- Gypsum, 6.7 mt/ha (3 T/A) + CaCl_2 , 17.2 mt/ha (7.7 T/A)
- Gypsum, 6.7 mt/ha (3 T/A) + H_2SO_4 , 12.3 mt/ha (5.5 T/A)

Table 12. Mean¹ pH values compared between years, Belle Fourche, SD².

Year	Depth (cm)	Treatment													
		no straw	control	irrgtn	gouge	manure		manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum		topsoil only	topsoil +irrgtn
						vertical	mulch					only	irrgtn		
80 86	0-5	6.9 7.2	7.4 8.0	7.8 8.0	7.5 7.7	7.8 8.2	7.2 B 8.9 A	7.3 5.4	7.4 7.8	6.9 B 7.9 A	7.1 4.9	7.1 A 4.4 B	7.3 B 8.8 A	7.3 8.6	
80 86	5-10	6.9 6.9	7.4 7.5	7.8 7.7	7.5 7.3	7.8 8.0	7.2 B 8.8 A	7.3 A 4.4 B	7.4 7.6	6.9 7.4	7.1 A 4.9 B	7.1 A 4.3 B	7.3 7.7	7.3 B 8.3 A	
80 86	10-20	6.9 7.5	7.4 7.3	7.8 7.1	7.5 7.2	7.8 7.9	7.2 7.8	7.3 5.7	7.4 7.3	6.9 7.3	7.1 6.7	7.1 5.9	7.4 7.2	7.6 8.1	
80 86	20-38	6.9 7.4	7.4 7.5	7.8 7.6	7.5 7.7	7.8 7.5	7.2 7.5	7.3 7.0	7.4 7.4	6.9 7.5	7.1 7.0	7.1 6.9	7.4 7.5	7.6 7.9	

¹ Mean of three replications.

² Statistically significant comparisons are identified by boxes. Mean values are significantly (P<.05) different if followed by a different letter.

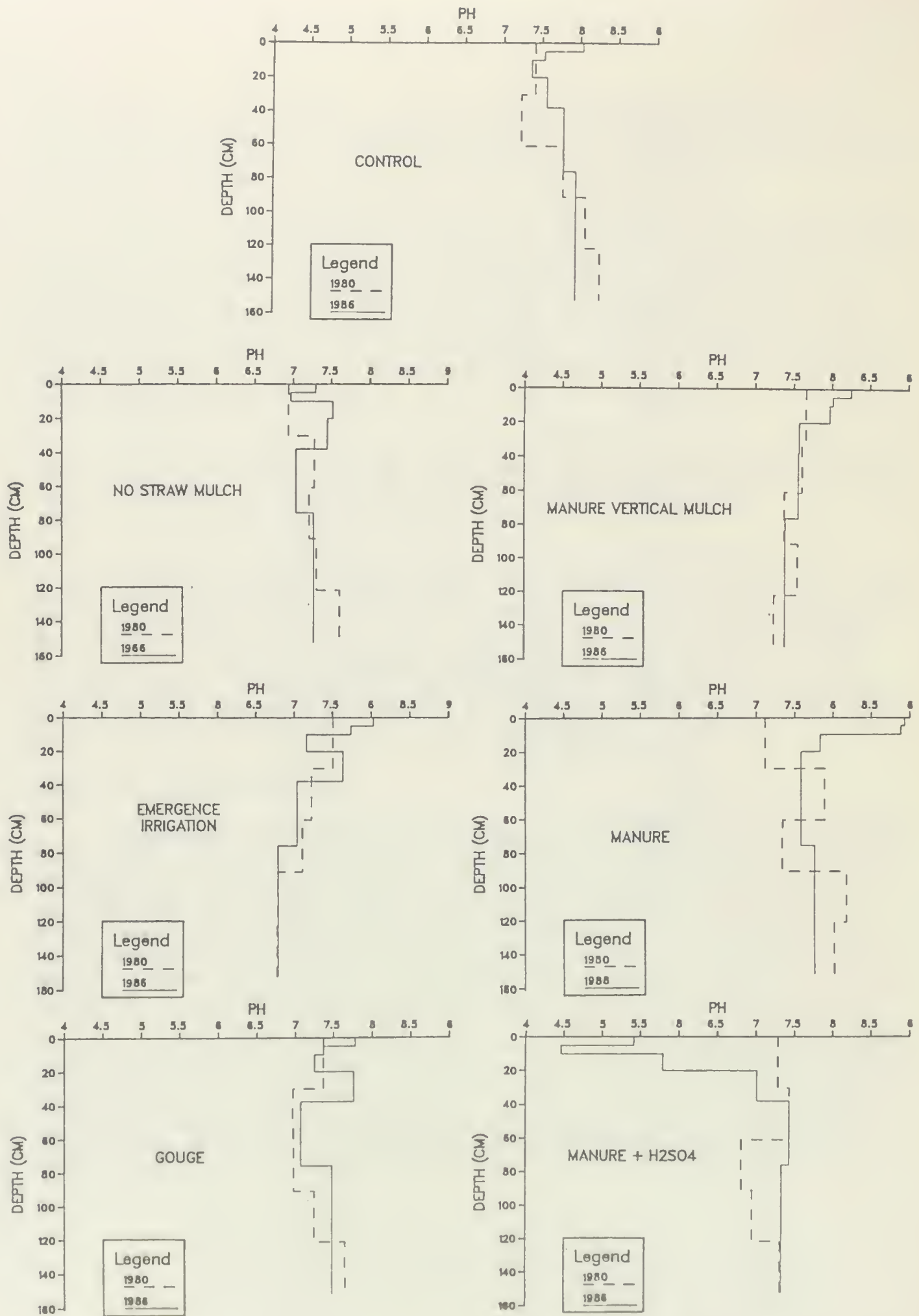


Figure 7. Spoil profile pH for amendment treatments in 1980 and 1986, Belle Fourche, SD.

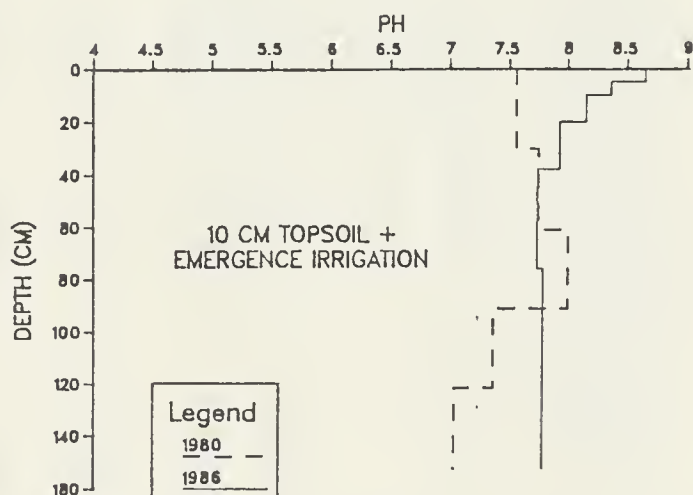
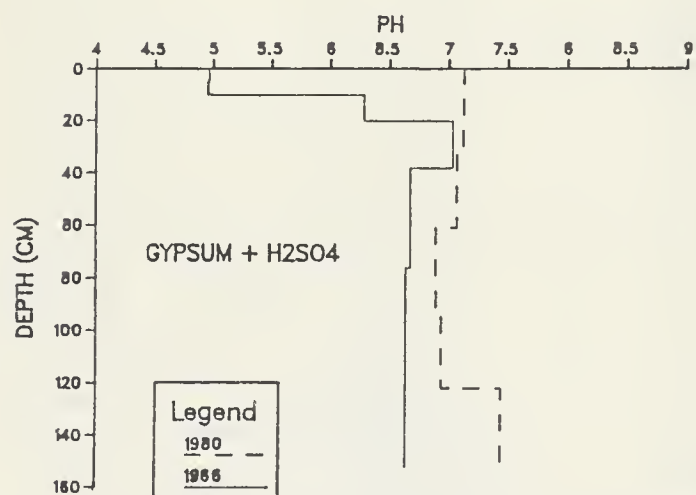
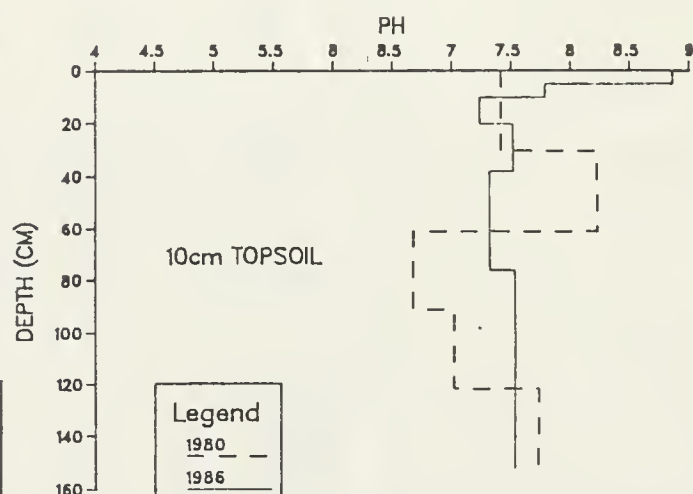
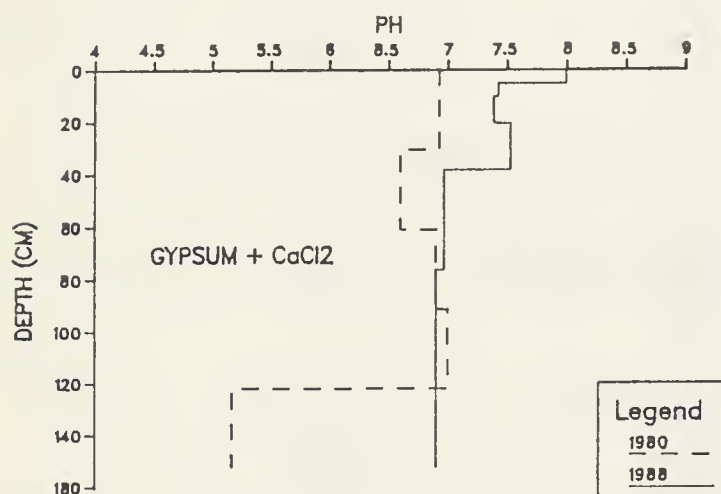
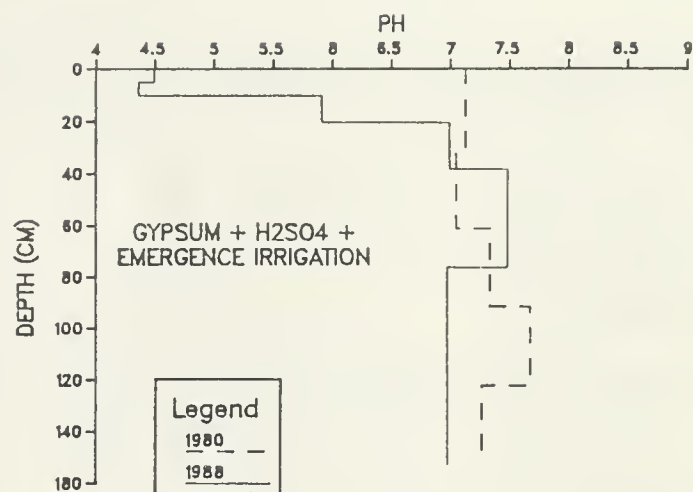
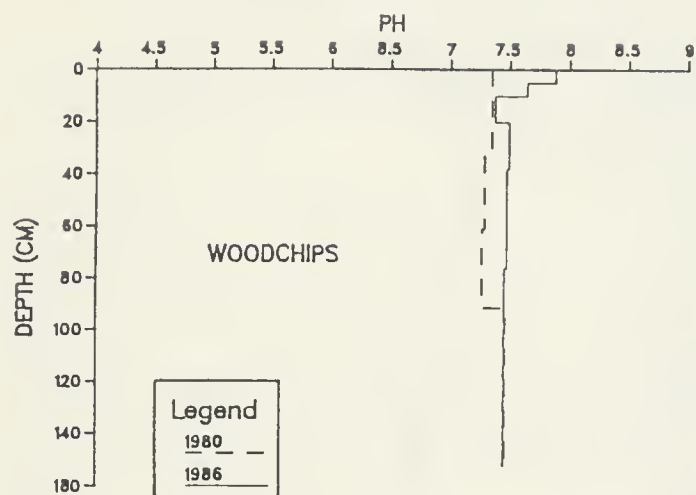


Figure 7. Continued.

Table 13. Mean¹ 1986 pH values, Belle Fourche, SD².

Depth (cm)	Treatment												
	no straw	control	irrigtn	gouge	manure vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +H ₂ SO ₄ +irrigtn	topsoil only	topsoil +irrigtn
0-5	7.2 B	8.0 AB	8.0 AB	7.7 AB	8.2 AB	8.9 A	5.4 C	7.8 AB	7.9 AB	4.9 C	4.4 C	8.8 A	8.6 A
5-10	6.9 C	7.5 BC	7.7 BC	7.3 BC	8.0 ABC	8.8 A	4.4 D	7.6 BC	7.4 BC	4.9 D	4.3 D	7.7 BC	8.3 AB
10-20	7.5 AB	7.3 AB	7.1 AB	7.2 AB	7.9 AB	7.8 AB	5.7 B	7.3 AB	7.3 AB	6.2 AB	5.9 B	7.2 AB	8.1 A
20-38	7.4	7.5	7.6	7.7	7.5	7.5 b	7.0	7.4	7.5 ab	7.0 a	6.9 ab	7.5 b	7.9
38-76	7.0	7.7	7.0	7.0	7.5	7.5 b	7.4	7.4	6.9 b	6.6 a	7.4 a	7.3 b	7.7
76-152	7.2	7.9	6.7	7.4	7.3	7.7 b	7.3	7.4	6.8 b	6.6 a	6.9 ab	7.5 b	7.7

1 Mean of three replications.
2 Statistically significant comparisons are identified by boxes. Upper case letters (horizontal boxes) show treatment comparisons. Lower case letters (vertical boxes) show depth comparisons. Mean values are significantly (P<.05) different if associated with a different letter.

Table 14. Simulated rainfall infiltration over a 30 minute period for bentonite minesoils.

Treatment*	% Infiltration of Total H ₂ O Applied			Mean ⁺ % Infiltration
	Rep 1	Rep 2	Rep 3	
No mulch	13.0	31.7	23.5	22.7a
Control	45.5	53.3	44.8	47.9bcd
Irrigation	38.6	42.8	39.5	40.3abc
Gouge	32.4	18.0	38.8	29.7ab
Vertical mulch	40.2	57.1	58.3	51.9bcd
Manure	95.1	98.5	92.9	95.5f
Manure + H ₂ SO ₄	29.5	19.5	38.0	29.0ab
Woodchips	95.8	57.1	94.6	82.5ef
Gypsum + CaCl ₂	87.6	90.5	88.2	88.8f
Gypsum + H ₂ SO ₄	39.2	92.4	64.9	65.5de
Gypsum + H ₂ SO ₄ + irrigation	39.3	54.0	40.7	44.7abcd
Topsoil	69.3	36.2	53.4	53.0cd
Topsoil + irriga- tion	53.3	18.9	39.6	37.3abc

* All treatments except as noted received straw mulch at 4.5 mt/ha (2.0 T/A).

⁺ Means followed by the same letter are not significantly different at the 95% level of confidence.

Table 15. Simulated rainfall infiltration rate after 30 minutes in bentonite minesoils.

Treatment*	Infiltration Rate, cm/hr			Mean ⁺
	Rep 1	Rep 2	Rep 3	
No mulch	0.1	1.5	0.0	0.5a
Control	2.5	3.9	2.0	2.8ab
Irrigation	1.4	1.3	1.0	1.2ab
Gouge	0.2	0.6	2.4	1.1ab
Vertical mulch	2.2	4.7	5.7	4.2bc
Manure	11.3	11.7	10.8	11.3e
Manure + H ₂ SO ₄	2.1	1.3	2.3	1.9ab
Woodchips	11.4	3.2	11.0	8.5de
Gypsum + CaCl ₂	10.3	10.6	9.6	10.2e
Gypsum + H ₂ SO ₄	3.2	10.3	6.9	6.8cd
Gypsum + H ₂ SO ₄ + irrigation	3.2	6.0	3.1	4.1bc
Topsoil	5.3	1.9	2.5	3.2ab
Topsoil + irriga- tion	2.1	0.9	1.3	1.4ab

* All treatments except as noted received straw mulch at 4.5 mt/ha (2.0 T/A).

⁺ Means followed by the same letter are not significantly different at the 95% level of confidence.

Each of these treatments had a moderately rapid infiltration rate (Table 16), which was on the average 3.3 times greater than the control. The infiltration rate on topsoiled mine-soils was not significantly different compared to the control, probably because the topsoil had become sodic and its clay content dispersed greatly upon being wetted.

An understanding of the mechanisms and pathways by which these chemical amendments reclaimed bentonite minesoils is presented in the discussion (Section 5.3). Before implementing or rejecting these results for field project work, the reader should understand the principles presented in the discussion.

5.2.3 Vegetation Responses to Chemical and Physical Bentonite Minesoil Amendments

5.2.3.1 Initial Plant Performance - 1980

Emergence density data indicated that either topsoil or woodchips provided the most favorable environment for germination and initial growth (Table 17). Substantial germination was also observed on the control, plots that were irrigated, and on the manure only treatment. Germination was poor to nonexistent on plots that did not have a surface mulch, on plots that received gypsum with H_2SO_4 , gypsum with $CaCl_2$, and on the manure + H_2SO_4 plot.

Emergence irrigation did not enhance plant density compared to the control. Emergence irrigation in combination with H_2SO_4 and gypsum did not improve plant density compared to the chemical application alone. When these sodic minesoils were topsoiled, emergence irrigation increased plant density by 40% the first growing season. This indicates emergence irrigation has merit when the root zone has no physical or chemical limitations. Without topsoil, emergence irrigation did not enhance first year plant density.

Table 16. Classification of infiltration rates (Soil Conservation Service, 1951).

<u>Descriptive Term</u>	<u>Infiltration Rate, cm/hr</u>
Very rapid	> 25.4
Rapid	12.7 - 25.4
Moderately rapid	6.3 - 12.7
Moderate	2.0 - 6.3
Moderately slow	0.5 - 2.0
Slow	0.1 - 0.5
Very slow	< 0.1

Table 17. Plant density by treatment and life form, July 1980, Belle Fourche, SD.

Treatment	Density (plants/m ²)				Total
	Grasses	Forbs	Legumes	Shrubs	
No mulch	0	0	0	0	0
Control	33	58	0	0	91
Irrigation	92	3	0	0	95
Gouge	25	16	0	0	41
Manure vertical mulch	0	33	0	0	33
Manure, 224 mt/ha	33	58	0	0	91
Manure, 112 mt/ha + H ₂ SO ₄	0	0	0	0	0
Woodchips	150	100	16	0	266
Gypsum + CaCl ₂	8	8	0	0	16
Gypsum + H ₂ SO ₄	0	16	0	0	16
Gypsum + H ₂ SO ₄ + irrigation	0	0	0	0	0
Topsoiled	167	83	0	0	250
Topsoiled - irrigated	167	183	16	0	350

These first year plant results reflect the rate at which each amendment was able to immediately modify the rooting environment. They are, therefore, biased in favor of topsoil and woodchip amendments. The topsoil treatment because the soil was the medium in which the seeded plants germinated and initially established roots, and the woodchip treatment because the woodchips immediately improved the physical structure of the spoils.

It is notable that density of grasses during the first growing season was zero (or near zero) for those plots treated with H₂SO₄. Minesoils treated with gypsum and CaCl₂ also had very low grass and forb establishment. The control had some grass establishment. Amendments were applied in April and plant density measured in July, 1980. This suggests that three months were not sufficient time for chemical amendments to change the physical nature of this minesoil. Based on these data, chemical amendments may have decreased plant density the first year, possibly due to increased minesoil salt levels and/or changes in minesoil pH that inhibited seed germination.

5.2.3.2 Plant Performance After Seven Growing Seasons - 1986

Total aboveground production averaged 1552 kg/ha across the thirteen treatments and ranged from 394 to 3169 kg/ha (Table 18). Perennial grasses, the dominant life form throughout the study area, had production values ranging from 230 to 3078 kg/ha. Canopy cover ranged from 6.9 to 71.9

Table 18. Mean¹ aboveground production and canopy cover by life form, July 1986, Belle Fourche, SD.

Plant Life Form	Aboveground Production (kg/ha)	
	Mean	Range
Perennial grasses	1308	230 - 3078
Annual grasses	101	6 - 523
Forbs	125	11 - 961
Shrubs	<u>2</u>	<u>0 - 16</u>
Totals	1552	394 -3169

	Canopy Coverage and Composition (%)	
	Absolute Cover	Range
Perennial grasses	41.6	6.9 - 71.9
Annual grasses	2.2	<0.1 - 8.5
Forbs	4.2	0.3 - 16.8
Shrubs	<u><0.1</u>	<u><0.2</u>
Totals	48.1	100.0

	Coverage	Relative Cover
Seeded Species	31.1	64.7
Volunteer Species	17.0	35.3

¹ Mean of the 13 experimental treatments.

percent. Shrubs were the least productive life form. Approximately 65 percent of the vegetation canopy cover in the study area was composed of seeded species.

Seeded plant species dominating the study site were western wheatgrass (Agropyron smithii Rydb.), tall wheatgrass (A. elongatum Host.), slender wheatgrass (A. trachycaulum (Link.) Malte), and prostrate kochia (Kochia prostrata (L.) Schrader) (Table 19). Other plant species with greater than 1.0 percent of the canopy cover were bearded wheatgrass (A. caninum (L.) Beauv.), foxtail barley (Hordeum jubatum L.), beardless ryegrass (Elymus triticoides Buckley), Japanese brome (Bromus japonicus Thunb.), and smooth brome (Bromus inermis Leys.).

Non-seeded species invaded from adjacent mineland or native rangeland, or were contaminants in the seeded mixture. Invaders that had substantial canopy coverage were Canada bluegrass, smooth brome, beardless wildrye, and foxtail barley (Table 19). There were 20 (70%) non-seeded species

Table 19. Mean¹ percent canopy coverage by species and treatments, June 1986, Belle Fourche, SD.

	Treatments													Mean
	deep chisel no straw	deep chisel (control)	deep chisel +irrgtn	gouge	manure vertical mulch	manure only	manure +H ₂ SO ₄	woodchips	gypsum +CaCl ₂	gypsum +H ₂ SO ₄	gypsum +H ₂ SO ₄ irrgtn	topsoil only	topsoil +irrgtn	
Perennial Grasses														
Agropyron caninum	0.4	0.2	0.4	2.9	4.5	5.0	4.7	4.7	0.2	7.8	5.5	4.9	4.4	3.5
Agropyron cristatum ²		0.9	0.8	1.3	0.7	1.6					0.5	1.6	3.7	0.8
Agropyron elongatum ²	2.8	1.9	7.2	1.7	8.1	18.9	1.9	22.9		6.2	8.0	4.0	1.5	6.6
Agropyron repens										1.0				0.1
Agropyron smithii ²	2.0	10.5	6.1	9.4	13.4	33.9	44.5	13.7	38.7	48.2	27.6	21.2	8.1	21.3
Agropyron spicatum			1.0	0.7	0.8								0.1	0.2
Agropyron trachycaulum ²	1.0	0.1			2.3	3.1	5.0	6.2	2.5	0.6	8.7		0.5	2.4
Bouteloua curtipendula ²													0.2	<0.1
Bromus inermis			1.0	0.1	0.3			3.0	2.5	2.3	2.8	1.2	1.3	1.3
Echinochloa crusgalli							2.9							0.1
Elymus triticoides					10.4		0.6	4.0		4.8	0.2			2.3
Hordeum brachyantherum							10.2		0.6					0.1
Hordeum jubatum					0.5		0.5		1.3	1.5	2.7	0.7	0.2	2.7
Koeleria cristata	0.7	0.4	0.7	0.7	19.2	4.9	1.6	0.7		0.2	1.3	<0.1	0.9	0.1
Poa sandbergia														<0.1
Poa specis									0.3				0.5	0.1
Sporobolus airoides ²		0.6												0.1
Annual Grasses														
Bromus japonicus	<0.1	0.3	1.1	1.0	1.0	8.5	0.3	0.1	2.6	1.8	1.1	4.2	6.3	2.2
Vulpia octoflora							0.3		<0.1	0.1	0.4	<0.1		0.1
Forbs														
Artemisia ludoviciana													0.2	<0.1
Chenopodium album		2.2	0.3	0.1	15.9	0.6		0.2	<0.1	<0.1	0.1	2.1	3.1	0.2
Kochia prostrata ²	8.6	0.1									<0.1			2.4
Hedeoma hispida						0.1		0.4			<0.1			<0.1
Melilotus officinalis ²													0.2	<0.1
Opuntia polycantha							4.7	0.1	<0.1	<0.1	0.6	<0.1	<0.1	0.7
Polygonum aviculare	1.7	0.1	0.8	0.9		0.3			0.2	0.8				0.1
Polygonum convolulus							0.6							0.1
Polygonum douglassii							0.1	0.7	<0.1					0.6
Unknown	0.1	1.9		3.8	1.0									
Shrubs														
Sarcobatus vermiculatus ²													0.2	<0.1

1 Mean of three replications

2 Seeded species

encountered compared to 9 (30%) seeded species. However, the non-seeded species only accounted for approximately 33% of the canopy cover.

5.2.3.3 Vegetation Response to Minesoil Amendments

After seven growing seasons, the manure treatments (i.e. vertical mulch, surface applied, H_2SO_4 combination) and gypsum in combination with either H_2SO_4 or CaCl_2 had aboveground plant production significantly greater than the control (Figure 8). There was no difference between surface applied manure tilled to a depth of 30 cm into the minesoil surface or placed in trenches (vertical mulch) to the 90 cm depth. Minesoils treated with either woodchips or topsoil had plant productivity that was not significantly different compared to the control. Mean plant production on woodchip treated plots was less than on plots treated with combinations of H_2SO_4 , CaCl_2 , gypsum and manure, but these differences were not significant except for the H_2SO_4 plus manure treatment. Surface gouging had no effect on plant production by the seventh growing season. Production on minesoils that did not receive a straw mulch during seeding was not significantly different compared to the control. The use of emergence irrigation for several weeks after seeding had no effect on plant production at year seven.

Plant canopy cover data supported similar results across treatments as that reported for productivity (Figure 9). Total production and canopy cover for the manure treatments averaged 2865 kg/ha and 77.3 percent, respectively (Appendix A, Tables 45 and 46).

Minesoils amended with inorganic chemicals (gypsum + CaCl_2 , gypsum + H_2SO_4 and gypsum + H_2SO_4 + irrigation) had plant production levels that were five times those found in the control. Mean production and canopy cover ranged from 1936 to 2497 kg/ha and 54.0 to 74.6 percent, respectively. Poor to non-existent initial plant densities on these treatments (1980) probably occurred because there had not been enough time for these applied chemicals to react in the spoil and thereby provide a suitable medium for germination and growth. There had been less than three months between amendment application and initial plant density estimates. Significant changes in spoil chemistry occurred during 1980 to 1986 that promoted substantial plant growth. In 1980, mean EC in the upper 20 cm of spoil averaged 7.1 mmhos/cm compared to 3.6 mmhos/cm in 1986 (Table 7). During this period, SAR decreased from an average of 39.8 to 13.7 (Table 4).

Although minesoils treated with woodchips and topsoil provided the best medium for seedling establishment in 1980 (see Table 17), after seven growing seasons, neither plant

* Total production values are significantly ($P \leq .05$) different if capped by a different letter.



Figure 8. Aboveground production by plant class and treatment, June 1986, Belle Fourche, S.D.

Treatments: 1 = no straw mulch, 2 = control, 3 = irrigation, 4 = gouge, 5 = vertical mulch, 6 = manure, 7 = manure + H_2SO_4 , 8 = woodchips, 9 = gypsum + $CaCl_2$, 10 = gypsum + H_2SO_4 , 11 = gypsum + H_2SO_4 + irrigation, 12 = topsoil, 13 = topsoil + irrigation.

* Total canopy cover values are significantly ($P \leq .05$) different if capped by a different letter.

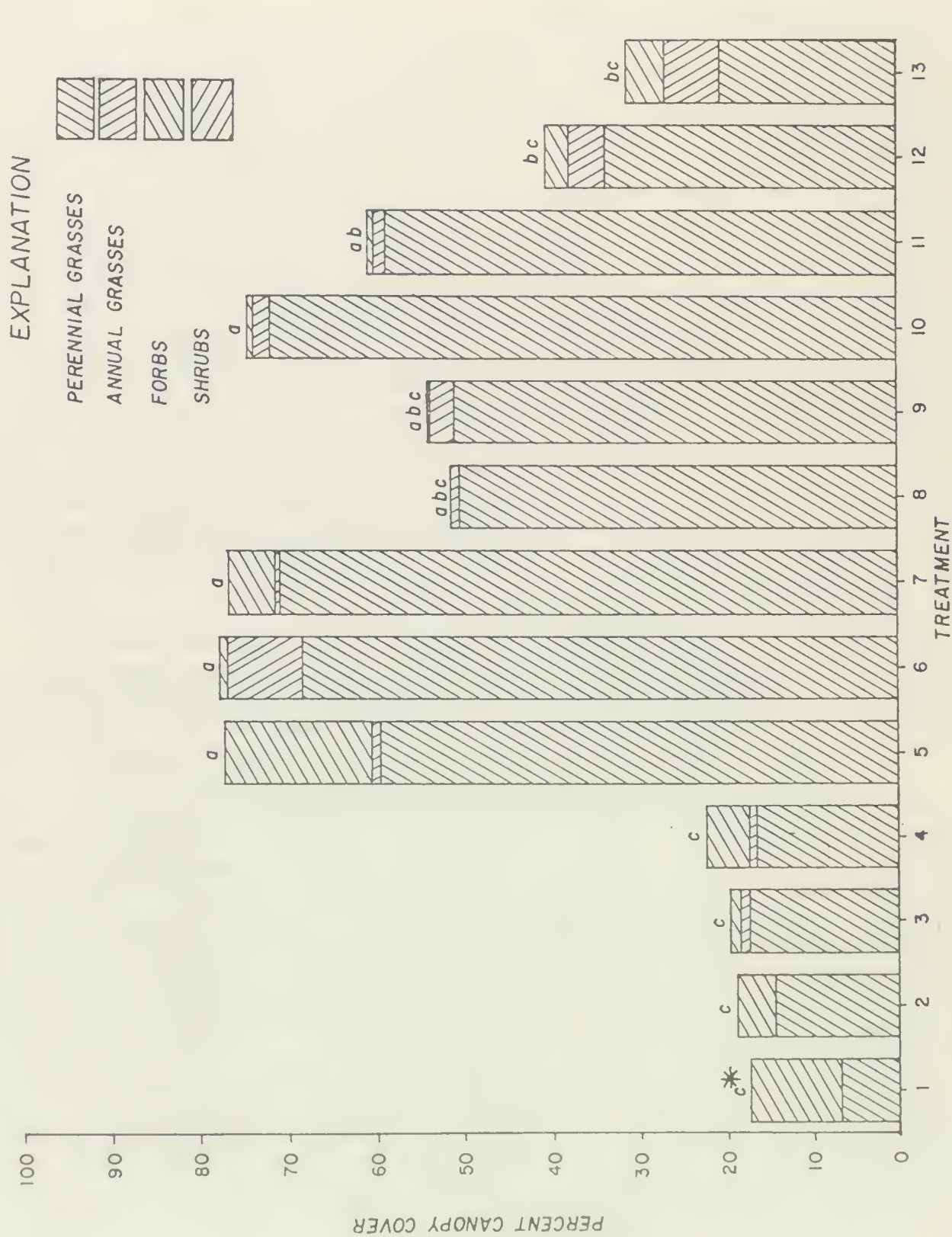


Figure 9. Canopy coverage by plant class and treatment, June 1986, Belle Fourche, S.D.

Treatments: 1 = no straw mulch, 2 = control, 3 = irrigation, 4 = gouge, 5 = vertical mulch, 6 = manure, 7 = manure + H₂SO₄, 8 = woodchips, 9 = gypsum + CaCl₂, 10 = gypsum + H₂SO₄, 11 = gypsum + H₂SO₄ + irrigation, 12 = topsoil, 13 = topsoil + irrigation.

production nor cover on these sites was significantly different from the control. Plant production on woodchip treated minesoils (1660 m³/ha) was also not statistically different compared to most manure or chemically amended plots. The one exception was for minesoils treated with manure and H₂SO₄ which had significantly better plant production compared to the woodchip treated plots. Apparently, the rapid sodification and salinization of the 10 cm topsoil application resulted in comparatively low plant production (853 kg/ha) and cover (36%) on these sites.

Gouging, no straw mulch and emergence irrigation resulted in poor plant performance in the seventh growing season. Production on these treatments averaged less than 500 kg/ha in 1986 (Figure 8). Cover averaged less than 25% in the same year (Figure 9). Production on these plots was significantly lower than the manure or the gypsum treatments, and was not significantly different compared to the woodchip and the topsoil treatments. Mean plant production on these plots was only about one-third that on woodchip plots, but this difference was not statistically significant. Canopy cover data revealed similar trends; significantly less cover than the manure or the gypsum + H₂SO₄ treatment, but similar cover to the woodchip, gypsum + CaCl₂, and the topsoil treatments. Water infiltration was less on these plots than any other treatment, including the unamended control.

Minesoils treated with gypsum in combination with H₂SO₄ had significantly greater root biomass compared to the control (Table 20). Root biomass in all other treatments was not statistically different compared to the control. However, manure alone and manure + H₂SO₄ treated minesoils had, on the average, 3.5 times as much root biomass as the control. All other treatments revealed root biomass levels very similar to the control.

5.3 DISCUSSION

5.3.1 Reclamation with Chemical Amendments

The potential of chemical soil amendments to mitigate sodic soil conditions in agriculture has long been recognized (ARS 1977; Fitts et al. 1943; Overstreet et al. 1951; Padhi et al. 1965; Van Schaik 1967; Pair and Lewis 1959; to name a few). Improvement of sodic minesoils with chemical amendments has been demonstrated in more recent years (Gould 1978; Sandoval and Gould 1978; Sandoval et al. 1973; Power et al. 1976; Dollhopf et al. 1980 and 1985).

Table 20. Root biomass (g/1000 g of soil), June 1986, Belle Fourche, SD.

Treatments	Root Biomass
No straw mulch	0.077 d ¹
Control	0.230 cd
Emergence irrigation	0.207 cd
Surface gouging	0.221 cd
Manure vertical mulch	0.227 cd
Manure	0.536 bcd
Manure + H ₂ SO ₄	0.564 bcd
Woodchips	0.260 cd
Gypsum + CaCl ₂	0.804 abc
Gypsum + H ₂ SO ₄	0.872 ab
Gypsum + H ₂ SO ₄ + irrigation	1.088 a
Topsoil	0.265 cd
Topsoil + irrigation	0.396 bcd

¹ Values followed by different letters are significantly different at the $P \leq 0.05$ level.

On these abandoned bentonite minesoils, gypsum in combination with either CaCl₂ or H₂SO₄ significantly decreased SAR, EC and increased plant production and infiltration. Six years after amendment application, crust forming characteristics of these minesoils were absent and a mellow-granular structure surface spoil suitable for plant growth was present. The addition of these amendments to the sodic minesoil had two effects that helped decrease the SAR and EC. All these amendments are in effect salts, and served to increase the soil salt content to such a level that flocculation of soil particles was enhanced by depressing the ionic double layer system associated with the clay particles. A flocculated sodic minesoil will tend to transmit water more efficiently and thereby enhance the salt leaching process. Second, these chemical amendments tended to increase the exchangeable and soluble Ca⁺⁺ in the sodic spoil, thereby decreasing the SAR. The manner in which these chemical amendments reacted in this sodic spoil are illustrated by reactions {1} and {2} (X = soil exchange complex).



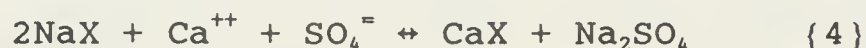
During 1980 to 1986, these reactions resulted in the minesoil SAR decreasing from approximately 40 to 9. The solubility of CaCl_2 (595 g/L) is nearly 250 times greater than gypsum (2.4 g/L) mined from the earth. When gypsum is applied as an amendment, much of it will remain nonreactive for decades of time, and it is of questionable value for mine land reclamation projects. That is, the low solubility of gypsum limits its ability to quickly decrease minesoil SAR, therefore, its value is minimal during the crucial initial years of plant establishment. Given this scenario, CaCl_2 is the amendment of choice, however, it is 500% to 1000% more expensive than gypsum. Combining amendments can optimize the cost: benefit relationship in minesoil reclamation (Prather et al. 1978). Gypsum is a low cost source of calcium but it needs to be applied in combination with a highly soluble source of calcium. For this reason, gypsum was not applied alone in this investigation, but was in combination with either CaCl_2 or H_2SO_4 .

5.3.2 H_2SO_4

The mechanism by which H_2SO_4 , in combination with either gypsum or manure, reduced the sodic hazard of this minesoil is one not often presented in soil science. This mechanism must be understood in order to properly implement this amendment at other abandoned mine sites. Sulfuric acid, in combination with either gypsum or manure, significantly reduced SAR and EC, and significantly increased infiltration rate, plant production, cover and root biomass. Given classical soil science principles, H_2SO_4 should not have worked since alkaline earth carbonates were absent in this minesoil. The application of a 10% solution of HCl to this minesoil (i.e. the fizz test) indicated alkaline earth carbonates were absent. The function of H_2SO_4 is to solubilize natural alkaline earth carbonates (e.g. CaCO_3) inherently present in the minesoil and produce gypsum according to reaction {3}. Gypsum then disassociates so that calcium can displace sodium from



the cation exchange capacity (X) by reaction {4}. Reactions {3} and {4} did not occur in this minesoil because alkaline earth carbonates were not present.

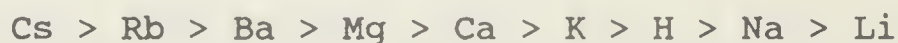


At first, it was thought that native gypsum present in the minesoil, as well as applied gypsum, was more rapidly solubilized by the addition of H_2SO_4 . Gypsum salts and crystals were observed in this minesoil before treatments were applied, and gypsum was also applied with H_2SO_4 as an amendment. When the combination of H_2SO_4 and gypsum was applied to this sodic

minesoil, it was possible that the H_2SO_4 increased the release of calcium from both the natural and applied gypsum. The Salinity Laboratory Staff (USDA 1954) presented reaction {5} to describe what may happen when H_2SO_4 and gypsum are applied to a sodic soil. Note that the products of reaction {5}

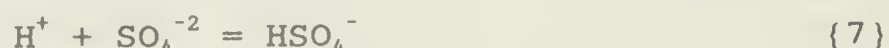
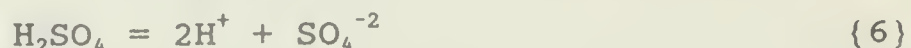


suggest 89% of the sodium displaced from the cation exchange capacity was a result of hydrogen exchange, and only 11% was attributable to calcium from gypsum. It is commonly known that the divalent calcium cation, with its small hydrated radius, can displace from the cation exchange capacity the monovalent sodium cation with its large hydrated radius. However, it is also well established that the hydrogen cation can displace sodium from the cation exchange capacity. These exchange conditions were defined by the extensive investigations of Schachtschabel (1940). He determined the relative displacement power of cations on the cation exchange capacity in montmorillonite clay was as follows. The influx of hydro-



gen onto the cation exchange capacity in proportion to calcium as indicated by reaction {5} should have notably reduced the minesoil base saturation, and consequently, the pH. Review of Table 12 shows minesoils treated with sulfuric acid in 1980 (pH 7.1-7.3) were very acidic (pH 4.3-5.4) in 1986 in the 0-10 cm depth.

However, it is unlikely that reaction {5} was the primary mechanism by which H_2SO_4 reduced the sodic hazard because the solubility of gypsum is not increased by the addition of H_2SO_4 , unless the pH remains below 2 (Lindsay 1979). Solubility diagrams of gypsum dissolution as a function of pH show that gypsum solubility is unaffected in the pH range 2 to 8, and decreases when pH exceeds 8. When H_2SO_4 undergoes dissociation {6}, it can form HSO_4^- {7} in an environment that



remains at pH less than 2. Gypsum in the presence of HSO_4^- will undergo dissolution but HSO_4^- is present only when the pH is less than 2. The pH of these minesoils treated with H_2SO_4 remained in the range of 4.3 to 5.4. Consequently, it is unlikely that the addition of H_2SO_4 to these minesoils caused the enhanced solubilization of either native gypsum or applied gypsum.

To further demonstrate that gypsum was not solubilized by H_2SO_4 , calcium and magnesium levels in the minesoil solution from 1980 (pre-treatment) and 1986 are presented in Table 21. Exchangeable cations were not determined, but these soluble levels should indicate the relative distribution of cations on the exchange sites. Calcium and magnesium levels were similar or often decreased from 1980 to 1986, which indicates very little, if any, calcium was being solubilized from either native or applied gypsum. Consequently, calcium from gypsum was not available to displace sodium from the minesoil exchange sites. However, sodium levels decreased notably in the 0-20 cm minesoil depth, and increased notably at minesoil depths greater than 38 cm (Table 21). This result indicates sodium was being displaced from cation exchange sites in the chemically amended zone, by cations other than either calcium or magnesium, and leached deeper in the profile.

The probable mechanism by which H_2SO_4 reclaimed these sodic minesoils was by solubilization of aluminum and iron from layer silicate minesoils. As H_2SO_4 underwent complete dissociation {6} when applied to this minesoil, the H^+ displaced some Na^+ from the exchange sites {8}. Hydrogen satur-



ated clays are not stable and tend to weather to Al- saturated clays because Al^{3+} is solubilized as the pH of the minesoil decreases. Solubilization of the Al^{3+} , as well as $\text{Al}(\text{OH})_2^+$ at minesoil pH levels near 5, will easily displace either Na^+ or H^+ from exchange sites, meaning conversion of a H- saturated clay to Al- saturated clay.

The decrease in minesoil pH from 1980 (7.1-7.3) to 1986 (4.3-5.4) resulted from an influx of aluminum onto the cation exchange sites. The tri-valent aluminum cation would tend to flocculate clay particles, a result that produced a non-crusting surface and a mellow-granular structure in this minesoil that was suitable for plant growth.

When H_2SO_4 was applied in combination with manure, the decrease in SAR from 34.8 to 8.8 during the seven year period was also due to displacement of sodium by hydrogen and aluminum (Table 21). Based on the above discussion, it can be hypothesized that H_2SO_4 can reclaim these sodic minesoils even when alkaline earth carbonates or calcium amendments are absent. However, this approach would be new and should first be field tested on minesoils without native gypsum present.

The low minesoil pH created by treatment with H_2SO_4 did not decrease plant performance at this site. Low pH, meaning high levels of hydrogen and aluminum, does not, in itself, cause a phytotoxic response. The secondary effects of low pH,

Table 21. Comparison of calcium, magnesium and sodium water extractable levels in minesoils from 1980 to 1986.

Minesoil Depth (cm)	<u>H₂SO₄ + Gypsum</u>			<u>H₂SO₄ + Manure</u>		
	Ca	Mg	Na	Ca	Mg	Na
	meq/L					
	1980					
0-30	5.7 ⁺	4.6	85.8	7.1	5.8	87.6
30-60	8.7	7.1	82.6	11.7	10.3	101.4
60-90	11.7	11.1	92.1	9.8	10.8	94.3
90-120	13.8	13.7	98.4	13.2	12.0	92.6
120-150	8.0	11.3	95.4	11.2	10.0	93.8
	1986					
0-5	4.0	1.5	9.8	8.3	5.5	14.4
5-10	2.8	1.4	23.6	8.7	5.2	21.8
10-20	10.4	5.2	50.0	5.0	3.6	42.5
20-38	15.9	11.4	96.6	11.9	8.6	81.3
38-76	18.4	17.6	124.6	14.8	12.5	125.3
76-152	20.1	19.6	126.2	16.2	15.4	106.4

⁺ Each table value is a mean of three replications.

that is, increased metal availability and low availability of essential plant nutrients, can limit plant performance. The excellent above ground and below ground plant growth after seven growing seasons indicates neither trace metals nor fertility will limit reclamation success on this minesoil.

At abandoned mine sites having no minesoil alkaline earth carbonates, it may be appropriate to apply H₂SO₄ in combination with limestone (CaCO₃, CaMg(CO₃)₂) instead of gypsum. In this manner, the sulfuric acid will react with the CaCO₃ (see reaction {3}) to produce gypsum, and some CaCO₃ may hydrolyze {9} to form OH⁻ and help prevent a significant decrease in



minesoil pH. The combination of H₂SO₄ and CaCO₃ was not field tested.

5.3.3 High pH Problems

Both manure alone and topsoil treated minesoils had undesirable pH levels greater than 8.5 to the 10 cm depth. The increased pH was likely due to sodium hydrolysis {10}. As



{10}

sodium migrated from spoils into topsoil by either diffusion or mass flow, (recall the SAR went from 1.0 to approximately 28 during the six year period), some of it formed sodium hydroxide in the topsoil and increased the pH. Application of manure also may have caused sodium hydrolysis {10} since manure contains appreciable amounts of sodium salts. Dollhopf (1975) analyzed feedlot manure from Montana and found 15,300 ppm, 9,900 ppm, 17,700 ppm and 7,000 ppm (dry weight) of calcium, magnesium, potassium, and sodium, respectively. The SAR in manure treated minesoils decreased from approximately 37 to 20 suggesting that calcium and magnesium from manure displaced sodium from the cation exchange capacity. Sodium displaced in this manure could have hydrolyzed and caused the increased minesoil pH.

Although manure application increased the pH to an undesirable level, plant production was excellent (see Figure 8). Therefore, this elevated pH level should not be considered a factor limiting reclamation. Plant performance on topsoiled minesoils was poor, but this was primarily due to high SAR conditions rather than the elevated pH.

5.3.4 Required Time Period for Chemical Amendment Reclamation

The poor to non-existent plant density measured three months after H_2SO_4 , CaCl_2 and gypsum had been applied indicates that chemical mitigation of the sodic problem was not immediate (see Table 17). Six years after amendment application, these chemically amended minesoils had a very mellow, water absorbing, granular-like soil structure in the 0-10 cm zone that no longer developed crusts or compacted layers limiting plant growth. It is not known when, meaning one year, two years, etc., these chemically amended minesoils became suitable for plant growth because test plots were not monitored during the 1980 to 1986 period. The test plot site was nearly level and, consequently, the lack of plant establishment during the first year did not result in severe erosion. Most abandoned mine sites are not level and erosion must be minimized the first year. The use of either wood-chips, coversoil, a mulch, manure, or surface manipulation in conjunction with chemical amendments will serve to enhance initial plant density and minimize erosion.

Plant density three months after gypsum, H_2SO_4 and CaCl_2 application was notably less than the control in 1980 (see Table 17). This was true even when H_2SO_4 was in combination with manure. This suggests that more time between amendment application and seeding may be desirable. In this regard,

amendment application during the fall season followed by seeding in the spring may minimize the adverse effects of chemical amendments on plant density.

5.3.5 Emergence Irrigation

Research in the semiarid Northern Great Plains has demonstrated that one month of temporary irrigation is beneficial to plant establishment on seeded minesoils (Young and Rennick 1982). After seeding in 1980, several bentonite minesoils were irrigated daily with 0.6 cm of water for 20 consecutive days. When irrigation was used in combination with H_2SO_4 and gypsum, plant density was zero three months after seeding (see Table 17). Apparently, keeping the chemically amended mine-soil wet for nearly a month after seeding did nothing to mitigate the adverse effects of these amendments on initial plant density.

Minesoils that were straw mulched, but received no amendment, had similar plant density values with or without irrigation. Daily watering likely exasperated the sodic clay system causing dispersion of the double layer and associated loss in soil physical conditions. Chemical amendments had not yet improved the sodic nature of these minesoils during the 20 days of irrigation, therefore, dispersion of the double layer occurred in the presence of these amendments. Irrigation for plant establishment had no merit on these sodic-clayey minesoils.

When the sodic minesoils were topsoiled, emergence irrigation increased plant density by 40% the first growing season. This indicates emergence irrigation has merit when the root zone has no physical or chemical limitations. Without topsoil, emergence irrigation did not enhance first year plant density.

5.3.6 Topsoil Use and Sodication

Topsoil applied to these sodic (SAR 33-37), clayey (60-68%) and smectite dominated clay mineralogy minesoils will quickly sodicate. When 10 cm of topsoil (SAR 1) was applied in 1980, it had become sodic (SAR 27) by 1986. Rapid sodication of topsoil has been measured in North Dakota where 30 cm of topsoil (SAR 1) was placed over sodic coal mine spoils (SAR 27). After three years, the 0-10 cm zone increased to SAR 10, and to 20 in the 20-30 cm zone. In order for salts to migrate from spoil into topsoil, the hydraulic conductivity of the topsoil/spoil profile must be very small so that drainage is limited. Merrill et al. (1980) suggested that minesoils with hydraulic conductivities of less than 0.002 cm/hour at a matric tension of 0.05 bars (near saturation), would be prone to topsoil sodication problems. A saturated hydraulic con-

ductivity of less than 0.002 cm/hour is classified (SCS 1983) very slow and is essentially impervious. The saturated hydraulic conductivity of these bentonite minesoils was 0.003 cm/hour, which is essentially impervious. The impervious nature of these minesoils means they will slowly wet-up in the spring and remain moist into the summer season. Although there is little soil water movement across the topsoil/spoil interface, the high water content provides a corridor for upward salt movement by diffusion. Diffusion was identified in North Dakota as the main mechanism by which salt migrated from spoil to topsoil.

Merrill et al. (1980) suggested that when a minesoil has characteristics favoring topsoil sodication by upward sodium diffusion that at least 100 cm of topsoil should be applied. Their theoretical calculations indicate that the upward salt diffusion process shall be largely confined to the 20 cm topsoil zone immediately above the sodic spoil. Therefore, a 100 cm thick topsoil application would theoretically have approximately 80 cm of topsoil relatively free from the encroachment of sodium salt diffusion. Dollhopf et al. (1985 and 1988) measured sodication rates in a Montana minesoil with 70 cm of topsoil. They found the 46 cm of topsoil nearest to the spoils was sodicating, but the top one-third of the topsoil had no sodication.

Abandoned minesoil reclamation rarely can apply more than 30 cm of topsoil since none was stockpiled for use during mining and cost is high to extract from nearby undisturbed sites. It can be assumed that if 30 cm of topsoil is applied, that two-thirds or more of it will sodicate in a few years. The top portion, perhaps 0-10 cm, will not sodicate. However, the topsoil will be largely ruined and it is likely that the cost:benefit ratio of this reclamation technique will not be favorable.

If abandoned minesoils can be reclaimed with 100 cm of topsoil, reclamation success should be assured. The present day bentonite mining industry salvages all the soil resource prior to mineral extraction, and most of their reclamation efforts with 60-100 cm of soil has been successful.

As demonstrated in this study, a 10 cm topsoil application quickly became sodic and plant production after seven growing seasons was not significantly different compared to the non-topsoiled control. The application of topsoil on abandoned minesoils is not recommended.

5.3.7 Application of H_2SO_4

When evaluating all the amendments on the basis of sodic minesoil remediation, enhanced plant production and product

cost, H_2SO_4 in combination with either gypsum or manure were the top performers. Application of CaCl_2 in combination with gypsum was equal to H_2SO_4 in combination with gypsum regarding sodic minesoil remediation and plant production, but CaCl_2 is approximately four times more expensive than H_2SO_4 .

Great quantities of high quality H_2SO_4 are manufactured in Montana which makes this chemical amendment a desirable choice for reclamation of these abandoned bentonite mine lands. However, there are no custom applicators of H_2SO_4 in our region. By comparison, in California and Arizona, custom applicators apply H_2SO_4 to thousands of hectares of sodic agricultural lands each year. They have developed large scale application equipment and this technology would need to be brought into this region.

5.3.8 Erosion Control

Woodchip treatment alone and topsoil application resulted in plant performance not significantly different compared to the control after seven years. However, these treatments enhanced plant density during the first growing season (1980). Similarly, the absence of a straw mulch resulted in plant performance not different compared to the control after seven growing seasons, but plant density was enhanced during the first growing season. Surface gouging did not enhance either plant density the first growing seasons or long-term plant performance.

Although these treatments did not produce long-term plant performance significantly better than the control, it must be emphasized that these plots were level and not prone to erosion. When chemical amendments are applied on mine land slopes, they should be in combination with either surface gouging, woodchips, straw mulch or manure to control erosion. Recall that data from this investigation suggest that chemical amendments will not mitigate the sodic minesoil conditions for at least three months and probably a year or more. Therefore, surface manipulation and/or an organic amendment will provide immediate erosion control during plant establishment.

5.4 SUMMARY

The effects of surface manipulation (straw mulch, gouging), chemical amendments (H_2SO_4 , CaCl_2 , gypsum), organic amendments (woodchips, manure), topsoil and emergence irrigation were evaluated on abandoned bentonite mined lands during a seven year period. Minesoils treated with H_2SO_4 in combination with either gypsum or manure, and minesoils treated with CaCl_2 plus gypsum, had sodic conditions significantly reduced from an SAR of approximately 38 to 8. These same treatments significantly increased both plant production and cover

compared to the control. These treatments also significantly decreased minesoil electrical conductivity and increased water infiltration rate.

Minesoils treated with woodchips and 10 cm of topsoil had plant production and cover not significantly different compared to the control. Mean plant production on woodchip treated plots was less than on plots treated with combinations of H_2SO_4 , CaCl_2 , gypsum and manure, but these differences were not significant except for the H_2SO_4 plus manure treatment. Topsoil having an SAR of 1 in 1980 was sodicated by 1986 (SAR 27) due to the upward migration of sodium from spoils into topsoil. Although application of manure did not reduce the sodic hazard to desirable levels, it significantly increased both plant production and cover compared to the control. There was no difference between surface applied manure tilled to a depth of 30 cm into the minesoil surface or placed in trenches (vertical mulch) to the 90 cm depth.

Although treatment with either woodchips, straw mulch, topsoil or gouging did not produce long-term plant performance significantly better than the control, the first three (not gouging) enhanced first year density. One or a combination of these treatments (or manure) should be in combination with chemical amendments to enhance initial plant density and control erosion. These data suggest that chemical amendments did not mitigate the sodic minesoil conditions for at least 3 to 12 months.

Sprinkler irrigation of these amended minesoils for a 20 day period after seeding had no effect on plant density on plots without topsoil. Plots with topsoil had a 40% increase in plant density due to emergence irrigation.

6.0 EFFECTS OF INDUSTRIAL WASTE PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE BRINE ON MINESOIL PHYSICO-CHEMISTRY AND VEGETATION DEVELOPMENT

The identification of low cost chemical amendments for abandoned bentonite minesoils is an important step in advancement of reclamation science. The purpose of this chapter is to present effects of two low cost amendments on minesoil physicochemical characteristics after 16 months of time. Plant performance in these amended test plots is also presented. These test plots, established in 1986, were located immediately adjacent to those plots established in 1980 and discussed in Chapter 5.0.

6.1 CHARACTERISTICS OF PHOSPHOGYPSUM AND MAGNESIUM CHLORIDE BRINE

Chemical amendments for use in bentonite reclamation must be both effective and economical. Reduction of ESP is necessary for reclamation success and lower amendment cost promotes utilization. Both phosphogypsum and magnesium chloride (MgCl_2) brine are produced as industrial by-products and create disposal problems at processing facilities. The use of these wastes to reclaim other disturbed sites produces a two-fold reclamation success.

Phosphogypsum and magnesium chloride brine are relatively untested as chemical amendments for use in reclamation. Recently, phosphogypsum was utilized as a bentonite spoil amendment in Wyoming (Anselmi 1986). Initial results appear promising, but long-term effectiveness is unknown. The only known field test of magnesium chloride for sodic soil reclamation occurred in the Soviet Union, again with promising results (Papinyan 1980). As spoil amendments, both materials contain divalent cations which should replace exchangeable sodium. Test plot evaluation in the Northern Great Plains is essential to document effectiveness in this environment. Potential adverse effects, should be identified before these amendments are included in a reclamation plan.

6.1.1 Phosphogypsum

Phosphogypsum is a by-product of the phosphate fertilizer industry. Phosphate ore containing calcium is processed with sulfuric acid (H_2SO_4). Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is precipitated as a silt sized (.002-.05mm) waste product. Phosphogypsum consists of the gypsum tailings material (80-99% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), mineral impurities, and less than 1% phosphate (P_2O_5) (Keren and Shainberg 1981). Thousands of tons are produced annually in the United States with no apparent market.

Radium 226 occurs in much of the phosphate ore from the Western United States. Phosphogypsum tailings produced in Idaho and Utah are reported to have radium 226 levels exceeding the U.S. EPA suspect level of 5 picocuries/gram (Range Inventory and Analysis 1986). In a Wyoming study, 12 inch incorporation of phosphogypsum amendment (35.5 mt/ha) with an average of 26 picocuries/gram radium 226, resulted in no significant increase in radium 226 levels compared to background levels (Range Inventory and Analysis 1986).

In semi-arid environments, dissolution of gypsum is slow when applied to non-irrigated sodic minesoils (Dollhopf et al. 1985). Because of the silt particle size, phosphogypsum has much more surface area than agricultural gypsum at a given fragment size (Keren and Shainberg 1981). These researchers found that due to the increased surface area, phosphogypsum has approximately ten times the dissolution rate as agricultural gypsum. Increased dissolution enables phosphogypsum to supply exchangeable calcium at a much faster rate.

Surface crusting from clay mineral dispersion often requires an amendment to reduce detrimental effects on seedling emergence and rainfall infiltration. Gal et al. (1984) reported that phosphogypsum application reduced clay dispersion at the soil surface helping to prevent crust formation.

The absence of severe surface crusts allows rainfall to infiltrate into the spoil. However, high sodium levels throughout the spoil profile restrict water movement following surface penetration. Upon initial wetting, the infiltration rate (IR) may appear normal but drop rapidly within minutes due to swelling processes. Kazman et al. (1983) reported that an incorporated phosphogypsum amendment prevented the sharp infiltration rate reduction at all tested levels of ESP. Incorporation of phosphogypsum into soils improves physical properties and promotes water infiltration (Keren and Shainberg 1981, Kazman et al. 1983, Gal et al. 1984).

6.1.2 Magnesium Chloride

Magnesium is the second most abundant exchangeable cation in soils but has received relatively little study compared to other cations (Bohn et al. 1985). As divalent alkaline earth metals, magnesium and calcium possess similar properties. Richards (1969) classified calcium and magnesium as similar ions important in the development of soil structure.

The effectiveness and unlimited availability of calcium chloride has made it popular as a sodic spoil amendment in recent years. In some instances, the relatively high cost of calcium chloride has been prohibitive. Similar properties give magnesium chloride the potential to be as effective as

calcium chloride in reclamation. Industrial processes result in magnesium chloride brine being available in a solution of approximate 32% purity (Redfern 1986).

Magnesium chloride effectively displaces sodium from the cation exchange complex (Petersen and Oad 1974, Arora and Coleman 1979). In field research, Papinyan (1980) reported significant soil ESP reductions using magnesium chloride amendments to reclaim sodic soils.

A "specific effect" of magnesium is the deterioration of structure in some magnesium saturated soils. Quirk and Schofield (1955) found that a magnesium saturated illite soil showed decreases in hydraulic conductivity when leached with distilled water. Further research indicated that the specific effect of magnesium is regulated by the ESP, dominant clay minerals, and electrolyte concentration of the solution. Rowell and Shainberg (1979) found similar hydraulic conductivity in sodium-magnesium and sodium-calcium systems when montmorillonite was the dominant clay. Rahman and Rowell (1979) stated that in a soil dominated by montmorillonite where clay swelling was the main mechanism causing conductivity changes, magnesium had no specific effect; the conductivity being simply controlled by the ESP and electrolyte concentration. Papinyan (1980) reported considerable improvements in soil-water relationships when magnesium chloride was used to amend sodic soils.

Plant growth is thought to be affected by the calcium:magnesium ratio in the soil. Bohn et al. (1985) stated that high magnesium concentration may repress calcium uptake. Application of magnesium chloride brine as an amendment will elevate magnesium levels and reduce the calcium:magnesium ratio. Although there is potential for plant growth problems due to increased magnesium levels, Simson et al. (1979) found that satisfactory plant growth could be maintained between calcium:magnesium ratios of 0.8 to 5.0. Hunter (1949) reported no yield influence on alfalfa within a calcium:magnesium ratio range of .25 to 32.

6.2 METHODS AND MATERIALS

6.2.1 Field Plot Design

During early May, 1986, implementation work began on the nearly level spoils (3% south) at the Belle Fourche study site. Two chemical amendments and 3 nitrogen fertilizer rates were to be tested within 6 test plots and 18 subplots (Table 22). The field plot design implemented was a split-plot with three replications (Figure 10). The ability to make long-term comparisons between newly implemented test plots, and the 1980 test plots (see Chapter 5.0), was a key objective of the field

Table 22. Chemical amendment and nitrogen fertilizer rate treatments at the Belle Fourche site.

TREATMENT	RATE
Phosphogypsum, 0-35cm	40.4 mt ¹ /ha/30cm (17.9 t/ac/ft)
Magnesium chloride brine, 0-35cm	36.2 mt/ha/30cm (16.1 t/ac/ft)
Subplots -- No N applied	0.0
N applied	67.0 kg/ha (60 lbs/ac)
N applied	134.0 kg/ha (120 lbs/ac)

¹ - Metric ton (2205 lbs.)

plot design. Although control plots for this site were established in 1980, no control plots were implemented for plots established in 1986 due to the lack of space at this location.

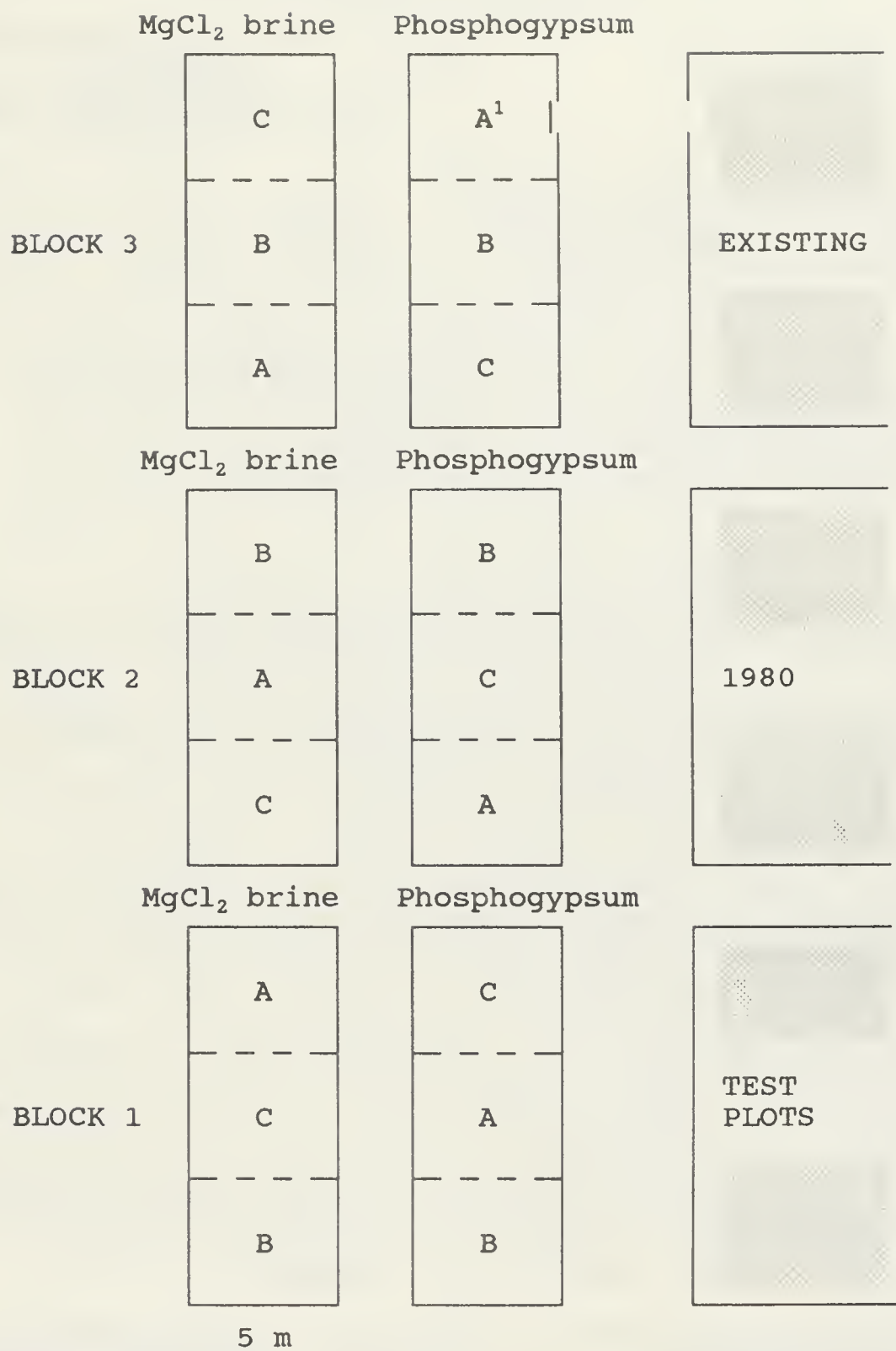
Test plots, 5 x 15 m were staked with a 2 m alley between replications. Each plot was divided into three, 5 x 5 m subplots for randomized nitrogen fertilizer rate treatments.

6.2.2 Amendments and Application Rate Determinations

Representative unamended spoil at the research site had a sodium adsorption ratio (SAR) of 33.8 (see Table 23). Exchangeable sodium percentage (ESP) and SAR are nearly identical in this range (Richards 1969). Therefore, ESP and SAR were considered equal for amendment rate calculations. Average spoil CEC at the site was 35.4 milliequivalents (meq)/100 g soil (Dollhopf and Bauman 1981).

Soils which have an ESP in excess of 15 are considered to be sodic (Richards 1969). To reduce minesoil sodium to a non-sodic level, a net decrease of 20.0 SAR (ESP) units was set as the reclamation goal on all treated test plots. To reach this goal, removal of 7 meq of exchanged Na/100 g soil was required. Replacement of 7 meq of sodium results in SAR reduction from 33.8 to 13.8 by the equations:

$$\begin{aligned}
 1) \quad \text{ESP (SAR)} &= 33.8 = \frac{11.9}{35.4} \begin{matrix} \text{(meq Na/100 g soil)} \\ \text{(CEC)} \end{matrix} \\
 2) \quad \text{ESP (SAR)} &= \frac{11.9}{35.4} - 7 = \frac{4.9}{35.4} \begin{matrix} \text{(meq Na/100 g soil)} \\ \text{(CEC)} \end{matrix} = 13.8
 \end{aligned}$$



¹ -- Letters denote subplot fertilizer rates. A denotes no N, B denotes 67 kg/ha, C denotes 134 kg/ha.

Figure 10. 1986 Field plot design at the Belle Fourche site.

Table 23. Representative values for unamended spoil chemistry at the Belle Fourche site.

SAMPLING UNIT	PARAMETER		
	SAR	EC (mmhos/cm)	pH
1980 Pre-amendment spoil (0-30cm) ¹	36.5	7.2	7.3
1986 Unamended control (0-35cm) ²	31.5	6.9	7.3
1986 Unamended spoil (0-35cm) ³	33.5	9.9	7.3
REPRESENTATIVE VALUES (mean)	33.8	8.0	7.3

¹ - Values represent the pre-amendment site mean obtained by analysis of 39 test plots (Dollhopf and Bauman 1981).

² - Values represent mean of 3 replications on 7 year old control plots (see Section 5.2.2.1).

³ - Mean values from spring, 1986 pre-amendment sampling.

Total element concentrations in phosphogypsum and magnesium chloride brine were determined by HNO₃ and H₂O₂ digestion (EPA 1987c). Phosphogypsum amendment used on the project had a CaSO₄ · 2H₂O content of 82.1% as determined by method 3050 (U.S. EPA 1982). The phosphogypsum was relatively fine textured with 87% passing a .149 mm (100 mesh) sieve. Moisture content of the amendment was 15% on a weight bases.

Mined (agricultural) gypsum solubility is 2.4 g/L in cold water (Weast 1986). Phosphogypsum has been reported to have ten times greater solubility compared to agricultural gypsum (Keren and Shainberg 1981). At a ten fold increase, phosphogypsum solubility is approximately 24 g/L in cold water.

In calculating test plot application rates, amendment purity and plot size must be considered. An amendment purity factor of 1.218 was used to compensate for 17.9% impurities in the amendment. The test plot size of 5 x 15 m was equivalent to .0075 hectare. An additional factor of 1.25 was used for the lack of quantitative replacement. This factor increases the application rate to account for incomplete exchange reactions between the amendment and the spoil.

One meq of exchangeable Na/100 g soil is replaced by 1.7 tons CaSO₄ · 2H₂O/acre-foot (Richards 1969). The metric conversion is 3.8 metric tons (mt) CaSO₄ · 2H₂O/hectare/30 cm.

Phosphogypsum plot requirement =

$$\begin{array}{rclcl} 7 \text{ (meq Na/100g)} & \times & 3.8 \text{ (mt/ha/30cm)} & = & 26.60 \text{ mt/ha/30cm} \\ 26.60 \text{ (mt/ha/30cm)} & \times & 1.25 & = & 33.25 \text{ mt/ha/30cm} \\ 33.25 \text{ (mt/ha/30cm)} & \times & 1.218 & = & 40.49 \text{ mt/ha/30cm} \\ & & & & (1.35 \text{ mt/ha/cm}) \\ 40.49 \text{ (mt/ha/30cm)} & \times & .0075 & = & \underline{.303 \text{ mt/plot/30cm}} \end{array}$$

Magnesium chloride brine was available for use as a spoil amendment. The brine used at the Belle Fourche site was determined to be 40.8% MgCl_2 by method 3050 (EPA 1982). The brine had a density of 1.3 kg/L and was shipped in 208 L (55 gallon) drums. Magnesium chloride solubility is 542 g/L in cold water (Weast 1986).

The quantity of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ that is equivalent to 1 ton of free S has been determined to be 5.38 tons (Richards 1969). To calculate an application rate for magnesium chloride brine, equivalent weights of MgCl_2 and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ can be related to solve for the quantity of MgCl_2 that is equivalent to 1 ton of free S. This quantity can then be multiplied by .32 tons to ascertain the quantity of MgCl_2 required to replace 1 meq of Na/100 g soil per acre-foot.

The quantity of free sulfur (S) required to replace 1 meq of Na/100 g soil has been determined to be .32 tons/acre-foot (Richards 1969). The mechanism of free sulfur replacement of sodium is oxidation of S to SO_3 , followed by reaction with water to form H_2SO_4 . Reaction of H_2SO_4 with soil CaCO_3 produces $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum), which solubilizes to release Ca^{2+} .

Calculations for the magnesium chloride brine requirement are presented. A factor for the lack of quantitative replacement was not used due to the liquid physical nature of the amendment. The amendment purity factor was 2.451 and the plot size was .0075 hectare.

$$\text{MgCl}_2 \text{ equivalent weight} = 47.61 \text{ g}$$

$$\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \text{ equivalent weight} = 86.10 \text{ g}$$

One ton of free S equals 5.38 tons $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

$$\text{Therefore: } \frac{86.10}{5.38} = \frac{47.61}{x}, \quad x = 2.97 \text{ tons MgCl}_2 \text{ is equiv. to 1 ton S}$$

$$\text{Relative to S: } .32 \times 2.97 = .95 \text{ tons MgCl}_2/\text{ac-ft to replace 1 meq Na/100 g soil}$$

Metric conversion: = 2.11 mt/ha/30cm

MgCl₂ brine plot requirement =

7 (meq Na/100g) x 2.11 (mt/ha/30cm) = 14.77 mt/ha/30cm

14.77 (mt/ha/30cm) x 2.451 = 36.20 mt/ha/30cm
(1.20 mt/ha/cm)

36.20 (mt/ha/30cm) x .0075 = .271 mt brine/plot
/30cm

Nitrogen levels on unamended spoil are typically low to moderate (Dollhopf and Bauman 1981). Nitrogen fertilizer (34-0-0), in the form of ammonium nitrate (NH₄NO₃), was tested for effects on seedling establishment. Each 5 x 15 m plot was subdivided into three, 5 x 5 m subplots. Treatment A was no N added; treatment B was 67 kg/ha; and treatment C was 134 kg/ha.

6.2.3 Field Plot Implementation

Following plot staking, two randomly located core samples were taken within the test plot area. Chemical amendments were manually applied and chisel plowed to a 35 cm depth. Plots were rototilled to a depth of approximately 20 cm to further incorporate the amendments.

All plots were broadcast seeded with 18 species chosen for saline-sodicity and/or drought tolerance (Table 24). Seeding rates for the forbs and warm season grasses were increased to prevent seed availability from being a limiting factor for these difficult to establish species. The total seeding rate was 84.1 kg of pure live seed (PLS)/ha.

Nitrogen fertilizer was broadcast onto the subplots at rates specified in Table 22. A wheat straw mulch was applied at the rate of 4500 kg/ha and stabilized by disk crimping. A two inch mesh fence enclosed all amended test plots.

For potential future comparisons, the design, amendment rates, seeded plant species and implementation procedures were as identical as practical to adjacent test plots implemented in 1980.

6.2.4 Minesoil Physicochemical Analysis

Core samples were collected in the spring of 1986 (prior to amendment application), fall of 1986, and summer of 1987 for physicochemical analysis. A Giddings core sampler was used in the field to take 4.8 cm diameter cores. Each core sample was divided into six depth increments of 0 to 5, 5 to 10, 10 to 20, 20 to 35, 35 to 70, and 70 to 140 cm. In the

Table 24. Plant species seeded in Spring, 1986 at the Belle Fourche site.

SPECIES	PLS/m ²
<u>Grasses</u>	
<u>Agropyron cristatum</u> (crested wheatgrass, var. Nordan)	105
<u>A. dasystachyum</u> (thickspike wheatgrass, var. Critana)	203
<u>A. elongatum</u> (tall wheatgrass)	60
<u>A. riparium</u> (streambank wheatgrass, var. Sodar)	128
<u>A. smithii</u> (western wheatgrass, var. Rosana)	92
<u>A. trachycaulum</u> (slender wheatgrass, var. Revenue)	256
<u>Bouteloua curtipendula</u> (sideoats grama)	267
<u>Sporobolus airoides</u> (alkali sacaton)	1703
<u>Forbs</u>	
<u>Achillea millifolium</u> (western yarrow)	3694
<u>Astragalus cicer</u> (cicer milkvetch)	228
<u>Linum lewisii</u> (Lewis flax, var. Appar)	391
<u>Melilotus officinalis</u> (yellow sweetclover)	137
<u>Petalostemum purpureum</u> (purple prairie clover)	825
<u>Ratibida columnaris</u> (prairie coneflower)	808
<u>Shrubs</u>	
<u>Artemisia cana</u> (silver sagebrush)	178
<u>Atriplex canescens</u> (fourwing saltbush)	34
<u>A. confertifolia</u> (shadscale)	17
<u>A. nuttallii</u> (Nuttall's saltbush)	87

spring of 1986, sampling consisted of taking two randomly located core samples within the test plot area following initial staking. The two core samples were composited into one sample for each depth increment. Results from spring, 1986 physicochemical analysis were used to help characterize unamended spoil at the study site.

Data collected in the spring of 1986 were used in combination with spoil chemistry data obtained from adjacent test plots to develop representative values for unamended spoil chemistry. Unamended spoil data from 1980 (Dollhopf and Bauman 1981), and unamended test plot data from the 1986 study (see Section 5.2.2.1) were also included. These data were

used to determine mean values for SAR and electrical conductivity (EC) that would be representative of unamended spoil across the entire research site.

In the fall of 1986, sampling consisted of removing two randomly located core samples from each test plot. The two cores were composited into one sample for each depth increment. An identical procedure was used to obtain core samples during the summer of 1987.

Core samples were prepared for analysis by air drying and weighing, followed by mechanical flailing. Particle size distribution was determined using a modification of the Day (1965) hydrometer technique. Textural class was determined using particle size distribution data and the USDA textural triangle (SCS 1951).

Electrical conductivity, pH, and SAR were analyzed in the aqueous extract of a saturated paste (Richards 1969). Using meq/L values obtained for Ca, Mg, and Na, SAR was calculated by the equation:

$$\text{SAR} = \text{Na} / (\text{Ca} + \text{Mg}) / 2$$

Saturation percentage, the percentage of water needed to saturate a soil paste, was determined for 1986 pre-amendment samples and 1987 test plot samples using methods 26 and 27b (Richards 1969). This parameter gives an indication of the clay content, clay mineralogy and swell potential of a soil material.

6.2.5 Infiltration Rate Study

On July 10 of 1987, infiltration rates were measured on the phosphogypsum and magnesium chloride brine treated plots, and at 3 random locations on unamended spoil directly adjacent to each treatment replication. An infiltrometer built from construction plans presented in Meeuwig (1971) was used to simulate rainfall. The infiltrometer was located at the 7.5 m point along diagonal transects within each test plot. A 48 x 48 cm runoff collection frame was positioned and tapped into the spoil to catch and funnel runoff into a container. Vegetation was clipped to ground level and all vegetative litter was removed.

Simulated rainfall was applied for 30 minutes at a constant rate of 12 cm/hr (Meeuwig 1971) and all runoff was collected. Runoff water was measured at the end of each 5 minute time interval. When necessary, plastic skirting was placed around the infiltrometer to reduce wind affects.

For each time interval, the volume of runoff collected was subtracted from the amount applied. The difference corresponds to the volume of water that infiltrated. This value was used to calculate an infiltration rate in cm/hr. An infiltration rate for each time interval was determined to evaluate infiltration rate reduction over time.

6.2.6 Vegetation Monitoring

Seedling density was measured on July 8, 1986, by counting individual seedlings within 20 x 50 cm microplots. Sampling of each subplot consisted of seedling counts in ten microplots spaced at 0.5 m intervals along a diagonal transect. Emergent seedlings were grouped into the classes of seeded grasses (perennial), annual grasses, seeded forbs and seeded shrubs. Annual grass is included as a plant class primarily for measurement of wheat (Triticum aestivum) seedlings which volunteered in substantial numbers from the applied wheat straw mulch.

Chemically amended bentonite spoil generally does not produce a favorable rooting medium during the first growing season due to inadequate amendment reaction time (Dollhopf et al. 1988). Emergent seedling density on the test plots was relatively sparse during the first growing season. For this reason, no other vegetation monitoring occurred until the summer of 1987.

Plant canopy cover and aboveground production were measured on July 7-9, 1987. Plant canopy cover was estimated using the Daubenmire (1959) technique on fifteen 20 x 50 cm microplots per test plot. Microplots were located at 1 m intervals along a diagonal transect. Plant categories were the same as established for seedling emergence except for the addition of a class for non-seeded forbs. By the second growing season, the annual forbs rillscale (Atriplex dioica) and burning-bush (Koshia scoparia) had invaded the test plots in considerable numbers.

Aboveground plant production was determined by clipping aboveground biomass within six 50 x 50 cm microplots per test plot. Microplots were located at 3 m intervals along a diagonal transect. Clipped vegetation was separated in the field into the same plant classes used for canopy cover. In the laboratory, samples were oven dried at 60°C for 72 hours and weighed to the nearest tenth gram.

6.2.7 Root Biomass Study

Two randomly located 0 to 35 cm core samples (4.8 cm diameter) were taken and composited from each test plot for

root biomass determination. Each composited core sample weighed approximately 2000 g.

In the laboratory, each sample was manually disaggregated and thoroughly mixed to create a homogeneous representation of the 0 to 35 cm depth. Samples were carefully split to obtain two representative 1000 g subsamples from each sample. Subsamples were soaked in a solution of .27% sodium hexametaphosphate for 24 hours to disperse the aggregates (Schuurman and Goedewaagen 1971). Dispersed subsamples were washed in a rotary root washing apparatus for 12 hours, or until all soil material had been removed. Coarse fragments were separated by decanting in water. The remaining organic material was dried at 70°C for 48 hours. Organic material other than root matter was manually separated. Dried root matter was weighed to the nearest 0.01 gram to determine root biomass/1000 g soil.

6.2.8 Statistical Analysis

To allow for statistical summarization and comparison, analysis of variance (ANOVA) was conducted on all data sets. Least significant difference (LSD) at a 95% confidence interval was calculated for mean values in each data set. Coefficients from LSD calculations are included in tables within the text. Data sets for canopy cover and above ground plant production had populations skewed to the left. To normalize population distributions for analysis of variance calculations, a logarithmic transformation of $\text{Log}_{10}(x + 1.01)$ was used (LeClerc et al. 1962).

6.3 RESULTS AND DISCUSSION

6.3.1 Amendment Trace Element Concentrations

In the phosphogypsum amendment, total silver (Ag) concentration was 15% greater than the suspected phytotoxic level (EPA 1987b). Total cadmium (Cd) and selenium (Se) concentrations were enriched above expected background levels in soil (Kabata-Pendias and Pendias 1984, Shacklette and Boerngen 1984). Total concentrations of the other analyzed trace elements were within the normal range for soils (Table 25). No enrichment of trace elements was detected in the magnesium chloride brine.

Assuming that 0.4 hectares - 30.5 cm of spoil weighs approximately 1792 metric tons, incorporation (35 cm) of the phosphogypsum amendment results in dilution of 40.4 mt into 4480 mt of spoil with 1 hectare. This represents a dilution ratio of approximately 110:1. Although several trace elements were enriched in the phosphogypsum, amendment dilution by incorporation clearly minimizes the potential for plant growth problems.

Table 25. Trace element total concentrations¹ in phosphogypsum and magnesium chloride brine amendments.

Element	Background Level-Source ²		Phytotoxic Level-Source		Phosphogypsum	Magnesium Chloride
Silver	.03-.09	g	2	b	2.3	.36
Aluminum	57,000	i	---		1380.0	.2
Arsenic	3.6-8.8	d	100	a	1.5	1.4
Barium	265-835	c	---		73.0	<1.0
Beryllium	1.6	c	10	f	<.5	.22
Cadmium	.07-1.1	c	100	a	10.0	.95
Cobalt	8.2	c	50	f	<1.0	.01
Chromium	20-85	d	100	f	34.0	.08
Copper	10-50	b	100	b	9.5	.3
Iron	27,500	c	---		330.0	28.8
Mercury	.04-.28	d	5	b	<.1	.004
Manganese	260-840	d	3000	e	3.3	1.32
Nickel	19	c	100	f	6.6	.08
Lead	17-26	d	1000	a	4.4	.06
Antimony	.9	c	10	f	<1.0	<1.0
Selenium	.2-.5	d	10	b	5.0	<.005
Tin	.6-1.7	d	50	f	<10.0	---
Thallium	.02-2.8	h	10	b	<1.0	.1
Vanadium	58	d	100	f	27.0	3.9
Zinc	34-83.5	d	500	a	37.0	4.0

¹ Concentrations are given in ppm on a dry weight basis.

² Source a is EPA (1987a); Source b is EPA (1987b); Source c is Kabata-Pendias and Pendias (1984); Source d is Shacklette and Boerngen (1984); Source e is Kovalskiy (1974); Source f is Kabata-Pendias (1979); Source g is Smith and Carson (1977a); Source h is Smith and Carson (1977b); and Source i is Tidball and Severson (1975).

Radium 226 occurs in much of the phosphate ore from the Western United States. Phosphogypsum tailings produced in Idaho and Utah are reported to have concentrations of radium 226 exceeding the U.S. EPA suspect level of 5 picocuries/gram (Range Inventory and Analysis 1986).

In a Wyoming study, 30 cm incorporation of phosphogypsum amendment (35.5 mt/ha) with an average of 26 picocuries/gram radium 226, resulted in no significant increase in radium 226 levels compared to background levels (Range Inventory and Analysis 1986).

6.3.2 Minesoil Physicochemical Characteristics

Spoil material at the study site was predominantly composed of the Belle Fourche Shale. The Munsell color of the Belle Fourche Shale is dark gray (7.5 YR 4/0). Mowry Shale occasionally occurs near the spoil surface, but is generally located in pit bottoms. The Munsell color of the Mowry Shale is light gray (7.5 YR 7/0).

Saturated paste extracts of the unamended spoil at the Belle Fourche site are characterized by high SAR and EC values, with near neutral pH (Table 23). Values for representative unamended spoil chemistry were developed using data obtained from the site (Table 26).

Core samples were collected and chemical analysis were performed for the 0 to 140 cm minesoil depth. Because chemical amendments did not impact the 35 to 140 cm depth zone, discussion was limited to the 0 to 35 cm depth. Data for the 35 to 140 cm depth is presented in Appendix A.

Representative unamended spoil SAR and EC over the depth of amendment incorporation (0-35 cm) was 33.8 and 8.0 mmhos/cm, respectively. Values for SAR and EC in this range represent very saline-sodic conditions.

Spoil saturation percentage prior to amendment application was 128 on the 1986 test plot area (Table 27). The mean pre-amendment saturation percentage was 126.6 on the 1980 test plot area (Dollhopf and Bauman 1981). Near identical saturation percentages on 1980 and 1986 test plots suggests similar clay content, clay mineralogy and SAR exist across the research site.

Mine spoil generated from the Belle Fourche Shale is dominated by clay size material. Dollhopf and Bauman (1981) reported that the clay mineralogy on adjacent test plots was dominated by smectite clay. High saturation percentage indicates similar clay mineralogy on the 1986 test plots.

Precipitation at the research site over the 14 month sampling period was 23% above normal (NOAA 1986, NOAA 1987).

6.3.3 Effects of Chemical Amendments on Minesoil Physicochemical Properties

6.3.3.1 Minesoil Sodium Adsorption Ratio (SAR)

In the fall of 1986, the SAR of saturated paste extracts from amended spoil (0-35 cm) ranged from 16.9 to 52.5 (Appendix A). At the 0 to 5 cm depth, magnesium chloride treated

Table 26. Unamended spoil chemical characteristics over time at the Belle Fourche site.

DEPTH (cm)	1980 WHOLE SITE PRE-AMENDMENT SPOIL ¹		
	SAR	EC (mmhos/cm)	pH
0-30	38.7	6.9	6.9
0-30	33.8	7.5	7.4
0-30	33.9	8.4	7.5
0-30	34.8	7.5	7.4
0-30	32.5	6.6	7.7
0-30	36.9	7.5	7.1
0-30	34.8	7.0	7.3
0-30	38.1	7.8	7.3
0-30	47.7	7.2	6.9
0-30	38.4	6.9	7.1
0-30	33.5	7.2	7.1
0-30	35.8	6.1	7.4
0-30	35.8	7.2	7.6
Site Mean (0-30cm)	36.5	7.2	7.3

1986 UNAMENDED CONTROL ²			
0-5	31.6	6.1	7.3
5-10	32.1	7.0	7.0
10-20	32.3	6.9	7.5
20-35	30.1	7.6	7.4
Mean (0-35cm)	31.5	6.9	7.3

SPRING, 1986 UNAMENDED SPOIL ³			
0-5	39.0	8.4	8.2
5-10	30.2	10.1	7.0
10-15	34.7	11.9	7.0
20-35	30.2	9.1	6.9
Mean (0-35cm)	33.5	9.9	7.3

¹ - Values represent the mean of 3 replications on pre-amendment test plots (Dollhopf and Bauman 1981).

² - Values represent the mean of 3 replications on 7 year old control plots (Dollhopf et al. 1988).

³ - Values for composited samples on spring, 1986 pre-amendment spoil.

Table 27. Spring, 1986 physical analysis of unamended spoil at the Belle Fourche site.

DEPTH (cm)	COARSE FRAGMENTS	SATURATION PERCENTAGE	PARTICLE SIZE DISTRIBUTION			TEXTURAL CLASS
			sand	silt	clay	
			%			
0-5	2	137	-	-	-	--
5-10	4	121	0	38	62	clay
10-20	7	123	3	45	52	clay
20-35	5	130	2	46	52	clay
Mean	4	128	2	43	55	

plots had a mean SAR of 20.4 (Table 28). This value was significantly lower than the mean SAR of 30.7 exhibited on phosphogypsum treated plots (0-5 cm). The SAR reduction on magnesium chloride plots suggests that this amendment is effective within 4 months following application. It is possible that during laboratory determination of SAR, performed on the water extract from a saturated paste, that chemical amendment solubilization was enhanced compared to the natural field condition. A determination of the exchangeable sodium percentage (ESP) would have indicated whether SAR values were accurately characterizing the sodic hazard, but this comparison was not performed.

Table 28. Fall, 1986 minesoil SAR values¹ at the Belle Fourche site.

TREATMENT	SAR			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	30.7 A ² a	31.6 Aa ³	28.4 Aa	29.3 Aa
Magnesium chloride	20.4 Ba	32.0 Aa	33.8 Aa	35.2 Aa

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

Reduction of SAR by 13.4 units on magnesium chloride treated plots (0-5 cm) indicates 67% effectiveness in attaining the SAR reduction goal during the first growing season. The SAR reduction of 33.8 to 30.7 on phosphogypsum treated plots (0-5 cm) corresponds to 15% effectiveness during the first growing season.

Lack of time and sufficient soil water moving through the minesoil profile is likely the reason that little change in SAR occurred with depth. Improvements in minesoil structure and permeability are necessary for surface water to infiltrate through the profile.

In the summer of 1987, minesoil sample analysis produced test plot SAR values ranging from 17.0 to 37.4 over the 0 to 35 cm depth (Table 48, Appendix B). No statistically significant differences in SAR were found between treatments or within treatment depths. Mean values for SAR at the 0 to 5 cm depth were 24.5 for phosphogypsum treated plots and 21.3 for magnesium chloride treated plots (Table 29). These values indicate considerable SAR reductions had occurred on amended test plots compared to the representative unamended spoil SAR of 33.8.

The SAR reduction of 9.3 units on phosphogypsum treated plots (0-5 cm) corresponds to 46% of the SAR reduction goal. Approximately one half of the applied phosphogypsum (0-5 cm) had reacted by the end of the second growing season (14 months). Smaller SAR reductions occurred with depth on phosphogypsum plots indicating that improvements in physicochemical properties occurred to a lesser degree over the 5 to

Table 29. Summer, 1987 minesoil SAR values¹ at the Belle Fourche site.

TREATMENT	SAR			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	24.5 A ² a	29.3 Aa ³	28.4 Aa	27.8 Aa
Magnesium chloride	21.3 Aa	26.3 Aa	26.3 Aa	31.7 Aa

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

35 cm depth. Inadequate soil water movement below the 5 cm depth apparently limited solubilization of the amendment which minimized sodium exchange reactions.

The SAR on magnesium chloride brine treated plots (0-5 cm) was reduced by 12.5 units 14 months after amendment application. This reduction indicates 62% effectiveness in attaining the SAR reduction goal. Over 5 to 20 cm, magnesium chloride was 37% effective by reducing SAR 7.5 units.

Overall, the SAR analyses indicates that after two growing seasons (14 months), both chemical amendments promoted improvements in minesoil SAR. A statistically significant SAR reduction at the 0 to 5 cm depth occurred on phosphogypsum treated plots in the summer of 1987 compared to the fall of 1986 (Table 30). This SAR reduction from 30.7 to 24.5 suggests that two growing seasons may be required for phosphogypsum to reduce SAR near the surface.

Magnesium chloride brine appears to be slightly more effective in reducing SAR (Figures 11-14). Dollhopf et al. (1985) found that highly soluble chemical amendments resulted in more rapid SAR reductions. Prompt dissolution enables amendments to react sooner within the spoil system. The liquid physical nature of magnesium chloride brine provides a temporary solution in the minesoil. Sodium replacement reactions are possible immediately following amendment application.

Table 30. Minesoil SAR values¹ over time at the Belle Fourche site.

DEPTH (cm)	PHOSPHOGYPSUM		MAGNESIUM CHLORIDE	
	1986	1987	1986	1987
0-5	30.7 a ²	24.5 b	20.4 a	21.3 a
5-10	31.6 a	29.3 a	32.0 a	26.3 a
10-20	28.4 a	28.4 a	33.8 a	26.3 a
20-35	29.3 a	27.8 a	35.2 a	31.7 a

¹ - Values represent the mean of 3 replications.

² - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

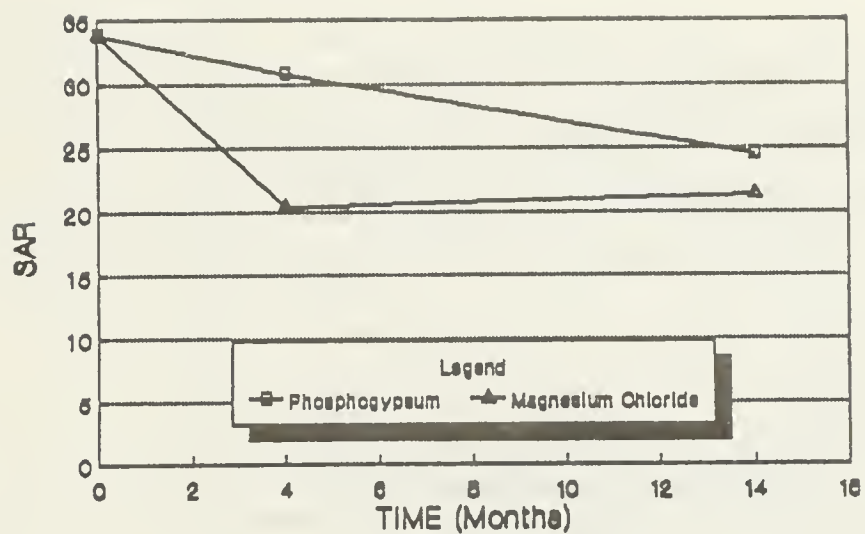


Figure 11. Minesoil (0-5 cm) SAR change over time at the Belle Fourche site.

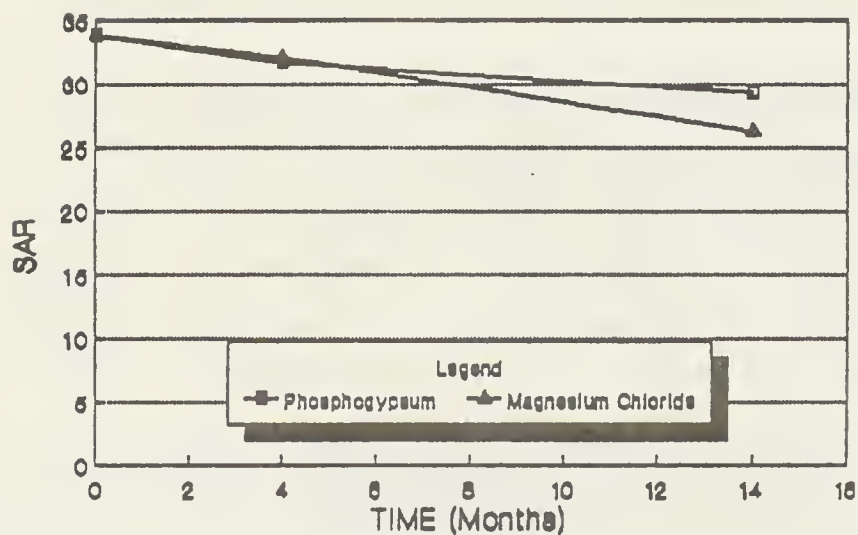


Figure 12. Minesoil (5-10 cm) SAR change over time at the Belle Fourche site.

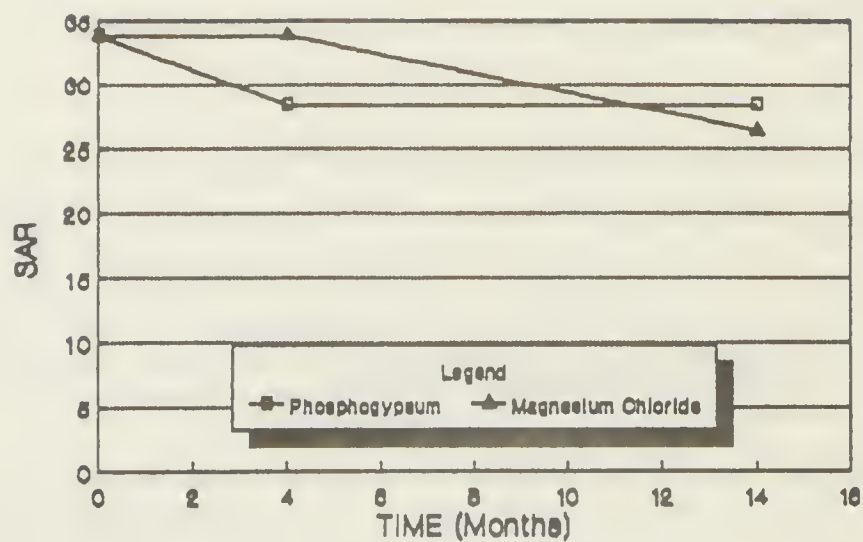


Figure 13. Minesoil (10-20 cm) SAR change over time at the Belle Fourche site.

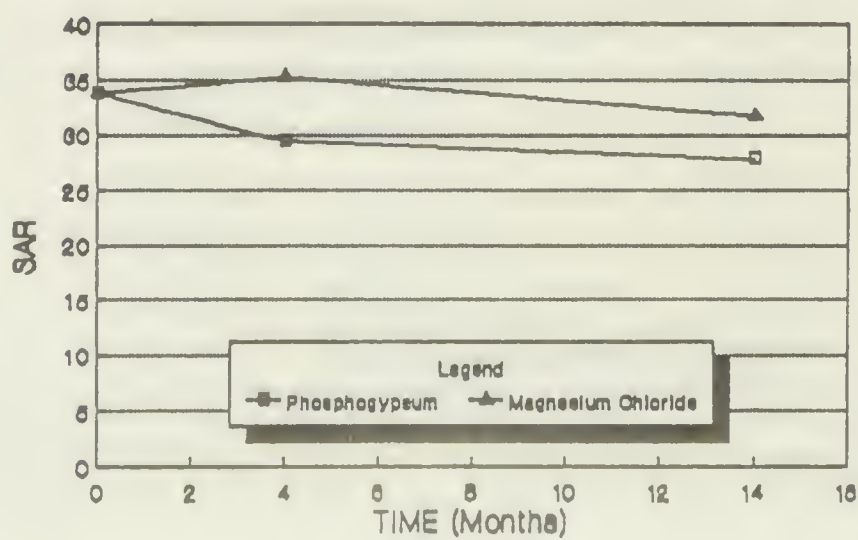


Figure 14. Minesoil (20-35 cm) SAR change over time at the Belle Fourche site.

The effectiveness of magnesium chloride brine in reducing SAR (0-5 cm) varied from 67% (4 months following application), to 62% (14 months following application). Notable effectiveness over 0 to 5 cm appears to be achieved within 4 months following application.

Several years may be required for either amendment to be effective at depth. This may be especially true with the phosphogypsum amendment due to relatively low solubility. Until surface water infiltrates deeper into the minesoil profile, phosphogypsum dissolution at depth will be inhibited. Although magnesium chloride brine is applied as a liquid, if soil water is limited, soluble magnesium salts will precipitate after a short time.

Minesoil SAR improvements were most apparent near the surface. As physical properties such as structure and permeability improve at the surface as a function of reduced SAR, more water will infiltrate into the profile. Progressively, minesoil physicochemical improvements should occur at depth as a function of increased infiltration.

A distinct moisture gradient was noted on the test plots. Block 1 plots (see Figure 11) received the most moisture, with block 3 plots receiving the least, and block 2 plots being intermediate. The mechanism was surface runoff from block 3, with accumulation in blocks 2 and block 1. The moisture gradient may have had an effect on the rate in which sodium exchange reactions occurred.

6.3.3.2 Minesoil Electrical Conductivity (EC)

Application of either phosphogypsum or magnesium chloride brine increased minesoil salinity levels compared to the unamended spoil EC value of 8.0 mmhos/cm. In the fall of 1986, EC values on phosphogypsum treated plots ranged from 7.1 to 11.8 mmhos/cm over the 0 to 35 cm depth (Table 47, Appendix B). The range on magnesium chloride treated plots was 6.5 to 22.0 mmhos/cm over the 0 to 35 cm depth. Mean EC values (0-5 cm) increased 39% on phosphogypsum plots and 112% on magnesium chloride plots compared to unamended spoil (Table 31).

At the 5 to 10 cm depth, EC was significantly greater on magnesium chloride treated plots compared to phosphogypsum treated plots. A 139% increase in salinity had occurred on magnesium chloride plots compared to a 36% increase on phosphogypsum plots. At the 10 to 20 cm depth, EC increased by 19% on phosphogypsum treated plots and 55% on magnesium chloride treated plots. Over the 20 to 35 cm depth, minimal changes in EC occurred on the chemically amended plots.

Table 31. Fall, 1986 minesoil electrical conductivity (EC) values¹ at the Belle Fourche site.

TREATMENT	EC (mmhos/cm)			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	11.1 A ² a	10.9 Aa ³	9.5 Aa	8.9 Aa
Magnesium chloride	17.0 Aa	19.1 Ba	12.4 Aab	7.6 Ab

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

No significant differences in EC were detected between depths on phosphogypsum treated plots. On magnesium chloride treated plots, EC was statistically greater over the 0 to 10 cm depth compared to the 20 to 35 cm depth.

Analysis from the summer of 1987 on phosphogypsum treated plots produced a range of EC values from 8.8 to 12.7 mmhos/cm over the 0 to 35 cm depth (Table 48, Appendix B). Magnesium chloride brine treated plots ranged from 10.1 to 22.1 mmhos/cm over the 0 to 35 cm depth. No statistically significant differences in EC were detected between phosphogypsum and magnesium chloride treatments, or within treatment depths (Table 32).

Electrical conductivity values on phosphogypsum treated plots were similar over the entire amended depth after 14 months. Mean EC (0-35 cm) was 10.8 mmhos/cm, indicating a 35% increase in salinity compared to pre-amendment levels.

A trend of consistently higher EC values on magnesium chloride treated plots compared to phosphogypsum treated plots was apparent 14 months following amendment application (Table 33). At the 0 to 5 cm depth, magnesium chloride plots were 57% higher in EC compared to phosphogypsum plots. Over the remainder of the amended profile, magnesium chloride plots were consistently higher than phosphogypsum plots in EC, but to a lesser degree than at the 0 to 5 cm depth. The mean EC range on magnesium chloride treated plots indicated that even after 14 months, salinity remained 60 to 99% higher than pre-amendment levels.

Table 32. Summer, 1987 minesoil electrical conductivity (EC) values¹ at the Belle Fourche site.

TREATMENT	EC (mmhos/cm)			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	10.1 A ² a	11.6 Aa ³	11.6 Aa	10.0 Aa
Magnesium chloride	15.9 Aa	14.0 Aa	12.8 Aa	12.9 Aa

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

Table 33. Minesoil electrical conductivity (EC) values¹ over time at the Belle Fourche site.

DEPTH (cm)	PHOSPHOGYPSUM		MAGNESIUM CHLORIDE	
	1986	1987	1986	1987
0-5	11.1 a ²	10.1 a	17.0 a	15.9 a
5-10	10.9 a	11.6 a	19.1 a	14.0 a
10-20	9.5 a	11.6 a	12.4 a	12.8 a
20-35	8.9 a	10.0 a	7.6 a	12.9 a

¹ - Values represent mean of 3 replications.

² - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

Although data is limited, there appears to be a trend of initial increase in EC near the surface of magnesium chloride brine treated plots, followed by a decrease over time (Figures 15-16). In addition, salinity appears to be increasing at the 10 to 35 cm depth (Figures 15-18). These changes in EC suggest that salts are being leached near the surface and accumulating deeper in the profile. However, continued monitoring of the test plots will be necessary to determine if preliminary trends continue over time.

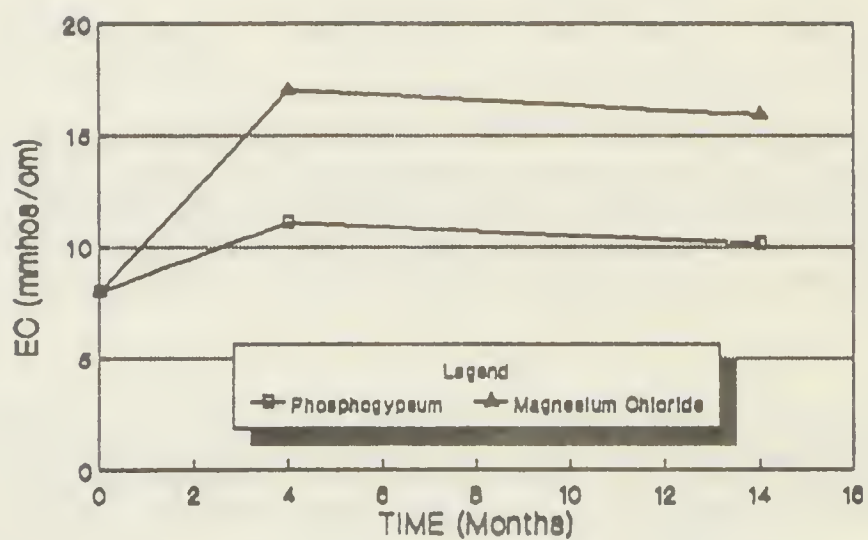


Figure 15. Minesoil (0-5 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

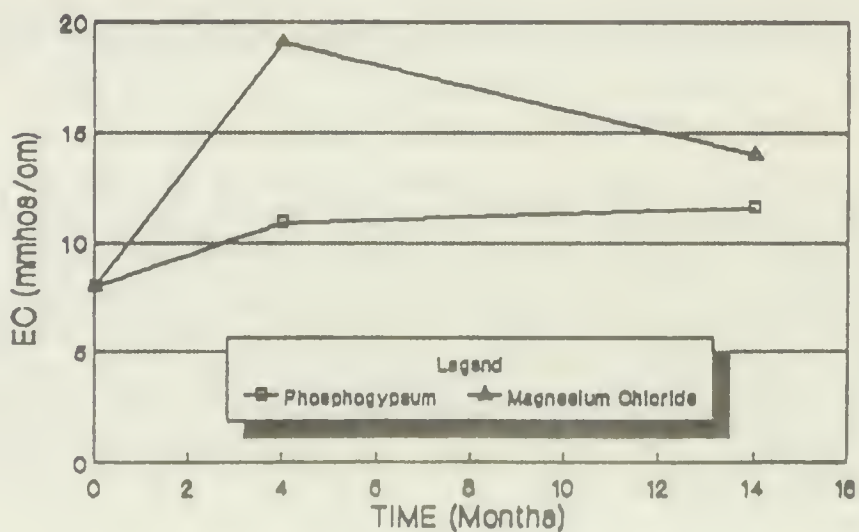


Figure 16. Minesoil (5-10 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

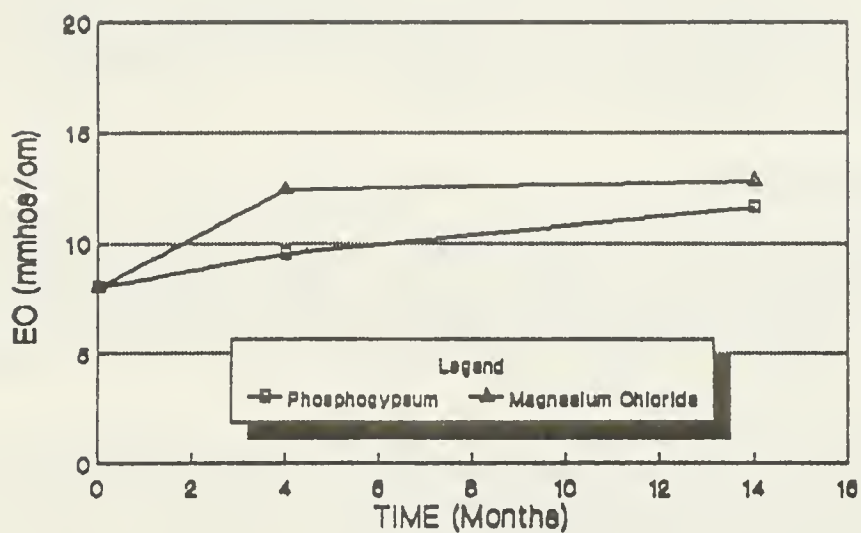


Figure 17. Minesoil (10-20 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

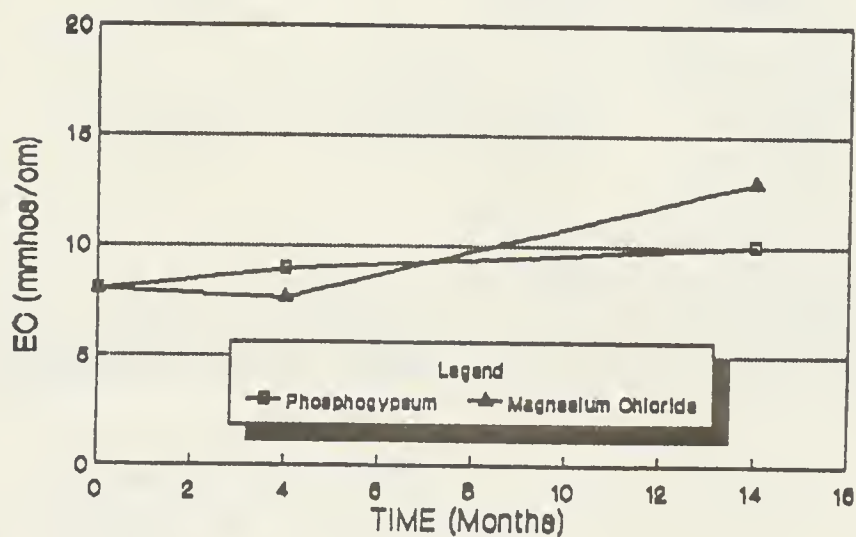


Figure 18. Minesoil (20-35 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

Plant growth is adversely effected by high salt concentrations due to osmotic stress (Bohn et al. 1985). The unamended spoil EC of 8.0 mmhos/cm indicates high salt concentration in the minespoil prior to amendment application. As a result of amendment application, salt concentrations increased above pre-amendment levels. Although high salinity inhibits water uptake by plants, there was a net improvement in the plant growth medium due to improved minesoil physical properties. High salt concentration and lower SAR result in reduced surface crusting and minesoil flocculation allowing precipitation to enter the profile.

6.3.3.3 Minesoil pH

Minesoil (0-35 cm) pH levels remained near neutral over the entire study period (Table 34). The range in pH values for the fall, 1986 sampling period was 6.4 to 7.8 (Table 47, Appendix B). The pH range for summer, 1987 sampling was 6.4 to 8.0 (Table 48, Appendix B).

A significant pH change over time was detected at the 10 to 20 cm depth on phosphogypsum plots between fall, 1986 and summer, 1987. This pH change from 6.6 in 1986, to 7.5 in 1987 was the only significant pH change and is difficult to attribute to the amendment. Natural variability in minesoil pH is likely the cause of differences in measured values.

Table 34. Minesoil pH values¹ over time at the Belle Fourche site.

DEPTH (cm)	<u>PHOSPHOGYPSUM</u>		<u>MAGNESIUM CHLORIDE</u>	
	1986	1987	1986	1987
0-5	7.4 a ²	7.5 a	7.1 a	7.0 a
5-10	6.8 a	7.3 a	6.8 a	6.9 a
10-20	6.6 a	7.5 b	7.1 a	7.0 a
20-35	7.1 a	7.3 a	7.1 a	6.9 a

¹ - Values represent the mean of 3 replications.

² - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

6.3.3.4 Saturation Percentage

Saturation percentage determinations were performed on core samples taken in the summer of 1987 to relate improvements in minesoil SAR to physical properties. Saturation percentage gives an indication of the severity of soil structure breakdown due to clay mineral dispersion. In a dispersed condition, pore space is reduced or eliminated decreasing water transmission through the minesoil. Reduced values for saturation percentage correspond with improved minesoil physical properties.

Mean saturation percentage was significantly less on magnesium chloride treated plots (0-5 cm) at 73, compared to 95 on phosphogypsum treated plots (Table 35). Compared to the unamended spoil saturation percentage of 128, these values indicate a 43% reduction on magnesium chloride plots and a 26% reduction on phosphogypsum plots.

At the 5 to 10 cm depth, saturation percentage on magnesium chloride treated plots was significantly less than phosphogypsum treated plots. A 16% decrease occurred on phosphogypsum plots (5-10 cm), while magnesium chloride plots were 37% less than the unamended spoil. Magnesium chloride plots exhibited reduced saturation percentage throughout the amended profile. Reductions of 30 and 26% were noted at 10 to 20 and 20 to 35 cm, respectively.

Within treatments, phosphogypsum treated plots were significantly lower in saturation percentage at the 0 to 5 cm depth compared to the 20 to 35 cm depth. Magnesium chloride treated plots did not significantly differ within the 0 to 35 cm depth.

Table 35. Summer, 1987 minesoil saturation percentage¹ at the Belle Fourche site.

TREATMENT	SOIL DEPTH (cm)			
	0-5	5-10	10-20	20-35
Phosphogypsum	95 A ² a	108 Aab	122 Ab	121 Ab
Magnesium chloride	73 Ba ³	80 Ba	90 Aa	95 Aa

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

Saturation percentage on amended test plots was reduced as a result of amendment application. Reductions suggest that the severity of swelling processes have been decreased. Mine-spoil with a saturation percentage greater than 85 is considered unsuitable for minesoil construction by some state mining regulatory agencies (MDSL 1983). Saturation percentage on magnesium chloride treated plots was less than 85 over the 0 to 10 cm depth. Although reductions in saturation percentage were substantial near the surface on phosphogypsum treated plots, the entire amended depth remained at a problem level.

6.3.4 Minesoil Infiltration Rate Study

The infiltration rate study was conducted to determine if the applied chemical amendments increased infiltration into the minesoil profile. Sodid mine spoils typically allow near normal infiltration initially, but exhibit dramatic infiltration rate reductions within a short time due to soil pore blockage from clay dispersion.

Simulated rainfall at a rate of 12 cm/hr over 30 minutes was used to mimic the short duration-high intensity thunder-showers common to the area. Infiltration rates in cm/hr were calculated at 5 minute intervals over a 30 minute period (Table 36).

Table 36. Summer, 1987 minesoil infiltration rates¹ over time at the Belle Fourche site.

MINUTES	INFILTRATION RATE (cm/hr)		
	Unamended spoil	Phosphogypsum	Magnesium chloride
0-5	8.5 A ² a	11.8 A b ³	11.1 A ab
5-10	3.2 B a	10.2 A b	6.8 B ab
10-15	1.3 BCa	6.3 B a	4.8 BCa
15-20	0.5 C a	4.9 BCb	4.4 C b
20-25	0.3 C a	3.5 CDb	4.0 C b
25-30	0.1 C a	2.8 D ab	3.8 C b

¹ - Values represent the mean of 3 replications.

² - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).

³ - Means followed by the same lower case letter in same row indicate no significant difference (P=0.05).

At 5 minutes after initial wet-up, infiltration rates for both the unamended spoil and the amended test plots were in the moderately rapid infiltration category (SCS 1951). Phosphogypsum plots had a significantly greater infiltration rate compared to representative unamended spoil.

Over the 5 to 10 minute time interval, swelling processes resulted in a 62% drop in infiltration rate to 3.2 cm/hr on unamended spoil. A 39% infiltration rate reduction occurred on magnesium chloride plots. Phosphogypsum treated plots maintained a significantly higher infiltration rate, with only a minor reduction of 13%.

During the 10 to 15 minute time interval, infiltration rates declined across all treatments. Unamended spoil declined to a value of 1.3 cm/hr. This value is representative of the moderately slow infiltration rate classification (SCS 1951). Although reductions were noted on chemically amended plots, they were not dramatic. Infiltration rates on phosphogypsum plots remained moderately rapid. Magnesium chloride plots were classified as moderate.

The 5 to 10, and especially the 10 to 15 minute infiltration rates demonstrate an important feature of the chemical amendments. High intensity rainfall events often last for at least this amount of time. By 10 to 15 minutes, minimal infiltration was occurring on unamended spoil. Nearly all precipitation was being converted to runoff. Erosion potential increased and moisture needed in the root zone was lost. Over the same time period, substantial infiltration was occurring on the amended test plots.

Between 15 and 20 minutes after initial wet-up, continued infiltration rate decreases occurred across all treatments. Phosphogypsum and magnesium chloride treated plots, while decreasing slightly, had stabilized at a level significantly greater than unamended spoil.

Infiltration rates remained relatively unchanged during the time intervals of 20 to 25 and 25 to 30 minutes. Rates of infiltration on unamended spoil were very near zero. Infiltration rates on chemically amended plots continued to decrease, but were statistically greater than unamended spoil. At 25 to 30 minute time interval, both phosphogypsum and magnesium chloride treated plots maintained moderate infiltration rates of 2.8 and 3.8 cm/hr, respectively.

Results from the infiltration rate study indicate that the combination of chisel plowing, chemical amendments, seeding, and a crimped straw mulch improved surface water infiltration into the minesoil (Figure 19). It is likely that a

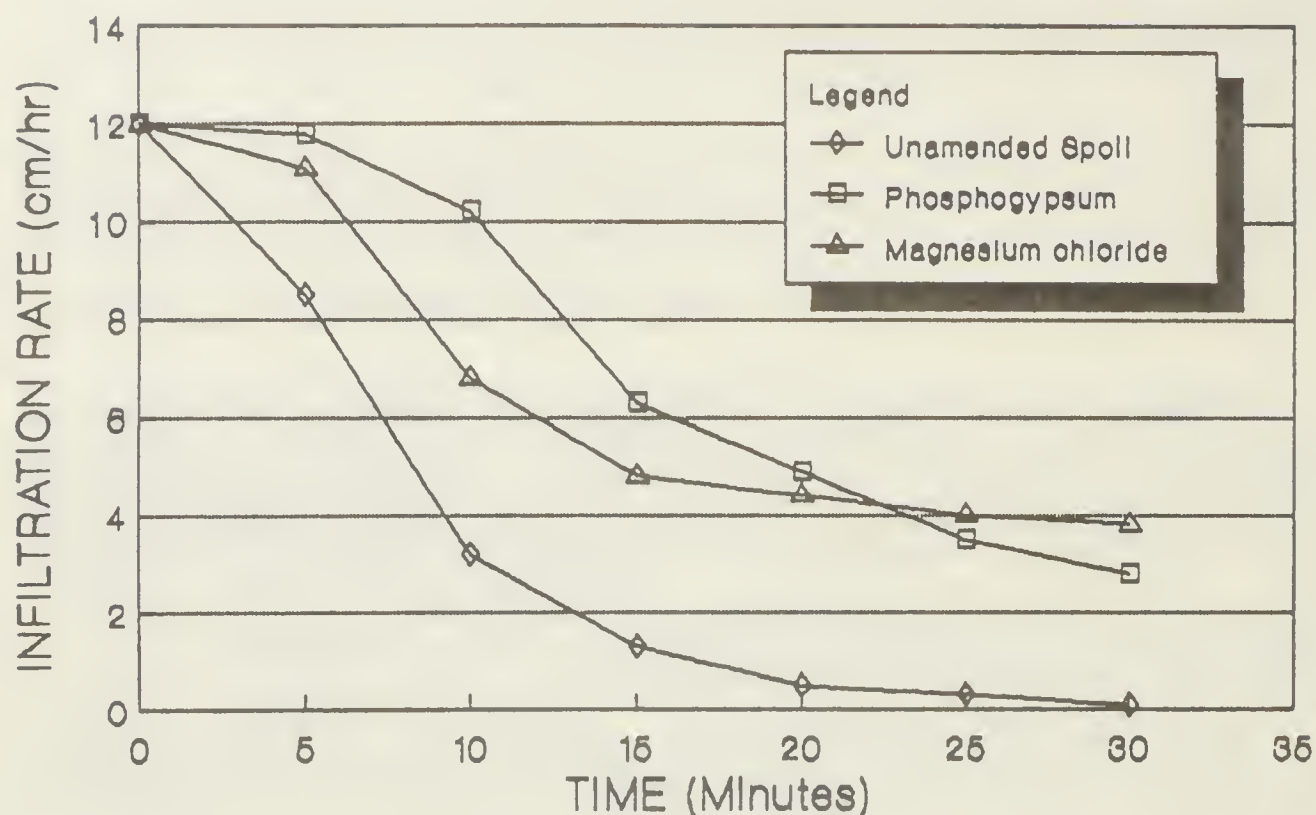


Figure 19. Minesoil infiltration rates over time at the Belle Fourche site.

majority of the improvement in infiltration is due to the application of the chemical amendments. The effects of plowing and mulch may be minimized after 14 months due to minesoil shrink-swell processes and mulch decomposition. Dollhopf et al. (1988) reported minimal infiltration rate improvement on adjacent test plots amended by chisel plowing, mulch, and seeding.

6.3.5 Vegetation Development

6.3.5.1 Seedling Density

Emergent seedling density was evaluated on amended test plots as a function of the chemical amendments and nitrogen fertilizer rates. All amended test plots exhibited seedling emergence. In comparing the treatments of phosphogypsum and magnesium chloride brine, emergent seedling density was significantly greater on magnesium chloride plots for seeded grasses, seeded forbs, and seeded shrubs (Table 37).

Table 37. Seedling density¹ (plants/m²) in 1986, by chemical amendment at the Belle Fourche site.

TREATMENT	SEEDED GRASS	ANNUAL GRASS	SEEDED FORB	SEEDED SHRUB	TOTAL
Phosphogypsum	47.3 b ²	75.3 a	19.0 b	1.5 b	143.2 a
Magnesium chloride	93.1 a	8.2 b	36.5 a	3.1 a	139.0 a

¹ - N = 3.

² - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

Density of annual grasses was significantly greater on phosphogypsum treated plots compared to magnesium chloride treated plots. Total seedling density did not significantly differ between chemical amendment treatments.

In comparing nitrogen rate treatments, total seedling density was significantly greater with 67 kg/ha nitrogen compared to the other nitrogen rates (Table 38).

Emergence of seeded grasses was significantly greater on subplots receiving 67 kg/ha nitrogen compared to the other nitrogen rates. There is little or no reason to believe that plant emergence can be influenced by nitrogen rate. This result suggests that some plant mortality may have already occurred by July 8, 1986, which could be influenced by nitrogen levels. Seedling density of annual grasses and seeded forbs did not significantly differ between nitrogen rate treatments. Density of seeded shrubs was significantly less on subplots receiving no nitrogen as compared to the other nitrogen rates.

Table 38. Seedling density¹ (plants/m²) in 1986, by fertilizer rate at the Belle Fourche site.

NITROGEN RATE (kg/ha)	SEEDED GRASS	ANNUAL GRASS	SEEDED FORB	SEEDED SHRUB	TOTAL
0	51.5 b ²	21.5 a	30.1 a	1.2 b	104.3 b
67	97.1 a	63.6 a	28.6 a	3.1 a	191.8 a
134	62.0 b	40.1 a	24.5 a	2.7 a	127.2 b

¹ - N = 6.

² - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

6.3.5.2 Canopy Cover

Plant canopy cover on the amended test plots in July of 1987 was dominated by the pioneering forbs, burning-bush and rillscale. These plants readily invaded the amended test plots. Rillscale is one of the few species that naturally exists on unamended bentonite spoil. Serving as a source of shade and protection to seeded vegetation, these forbs are welcomed early successional species. Neither rillscale nor burning-bush were observed during the 1986 seedling emergence period.

Total plant canopy cover was statistically greater on magnesium chloride brine treated plots compared to phosphogypsum treated plots (Table 39). Canopy cover of non-seeded forbs was also significantly greater on magnesium chloride treated plots. No other significant differences between treatments were detected in canopy cover by plant class.

Canopy cover on all test plots was generally greatest for non-seeded forbs and seeded grasses. Members of every plant class were established and contributed to canopy cover across all test plots.

6.3.5.3 Above Ground Plant Production

Above ground plant production on the study plots was dominated by burning-bush and rillscale. On disturbed sites, annual species often dominate vegetation temporarily. Within

Table 39. Summer, 1987 percent canopy cover¹ at the Belle Fourche site.

PLANT CLASS	TREATMENT			
	Phosphogypsum		Magnesium chloride	
Seeded Grass	7.5	a ²	6.4	a
Annual Grass	2.6	a	3.0	a
Seeded Forb	0.9	a	2.4	a
Non-Seeded Forb	15.2	b	26.7	a
Seeded Shrub	2.5	a	0.8	a
Total	28.6	b	39.3	a

¹ - N = 3.

² - Means followed by the same letter in the same row indicate no significant difference (P=0.05).

several years, perennial species typically replace annuals and become dominant.

Based on field observations, some plant species, particularly yellow sweetclover (Melilotus officinalis), suffered grasshopper damage. These insects reduced measurable seeded plant production.

Total production on phosphogypsum treated plots was not significantly different from magnesium chloride treated plots (Table 40). Non-seeded annual forbs contributed 60% of the total production on phosphogypsum treated plots and 83% on magnesium chloride treated plots. Total above ground production of seeded species was 694.7 kg/ha on phosphogypsum treated plots and 446.0 kg/ha on magnesium chloride treated plots. Production of annual grasses (e.g. Bromus japonicus, Vulpia octoflora) was significantly greater on phosphogypsum treated plots compared to magnesium chloride treated plots. Non-seeded forb production was significantly greater on magnesium chloride treated plots.

Seedling density, canopy cover, and above ground production were positively affected by the addition of chemical amendments. Unamended spoil at the research site is nearly devoid of vegetation.

6.3.5.4 Root Biomass

Root biomass per 1000 g soil over the 0 to 35 cm depth zone was determined by weighing root material extracted from core samples. Root biomass was significantly greater on magnesium chloride treated plots compared to phosphogypsum

Table 40. Summer, 1987 plant production¹ (kg/ha) at the Belle Fourche site.

PLANT CLASS	TREATMENT			
	Phosphogypsum		Magnesium chloride	
Seeded Grass	326.8	a ²	230.8	a
Annual Grass	286.4	a	63.6	b
Seeded Forb	35.5	a	7.6	a
Non-seeded Forb	1058.4	b	2271.2	a
Seeded Shrub	46.0	a	144.0	a
Total	1753.1	a	2717.2	a

¹ - N = 3.

² - Means followed by the same letter in the same row indicate no significant difference (P=0.05).

treated plots (Table 41). Observation of root sample cores revealed that minimal root material was present. This was due, at least in part, to the root study being conducted a short time following plot implementation. Minesoil physicochemical improvements are incomplete resulting in limited root development.

Table 41. Summer, 1987 minesoil root biomass (g/1000 g soil) at the Belle Fourche site.

BLOCK	OBSERVATION	TREATMENT	
		Phosphogypsum	Magnesium chloride
1	1	.11	.26
1	2	.17	.36
2	1	.08	.08
2	2	.09	.09
3	1	.06	.04
3	2	.06	.04
Mean		.09 b ¹	.14 a

¹ - Mean values followed by the same letter in the same row indicate no significant difference (P=0.05).

6.4 SUMMARY

6.4.1 Minesoil Physicochemical Response

Application of either phosphogypsum (40.4 mt/ha) or magnesium chloride brine (36.2 mt/ha) resulted in bentonite mine-soil SAR reduction near the surface. Four months following amendment application, mean SAR on magnesium chloride brine treated plots (0-5 cm) declined from an unamended spoil SAR of 33.8, to 20.4. Sodium adsorption ratio on phosphogypsum treated plots (0-5 cm) was significantly greater at 30.7. Fourteen months following amendment application, mean SAR (0-5 cm) on magnesium chloride treated plots was 21.3, and 24.5 on phosphogypsum treated plots. These results suggest that application of either amendment will result in SAR reduction. However, SAR reduction occurs more rapidly with magnesium chloride brine.

Several growing seasons may be required for improvements in minesoil physicochemical properties to occur throughout the root zone. Beneath the 20 cm depth, only minimal SAR reduc-

tions resulted from application of either amendment. Amendment incorporation with a chisel plow and rototiller was apparently accomplished to the 20 cm depth.

Overall, magnesium chloride brine was slightly more effective than phosphogypsum in reducing SAR and saturation percentage over the test period. Superiority of the more soluble amendment in promoting initial spoil physicochemical improvements was demonstrated.

An initial rise in EC near the surface occurred following application of phosphogypsum or magnesium chloride brine. Four months following amendment application, EC (0-10 cm) increased an average of 37% on phosphogypsum treated plots and 125% on magnesium chloride treated plots. After two growing seasons (14 months), a possible trend of EC reduction near the amended surface was noted. However, limited data makes this trend difficult to confirm.

Minesoil infiltration rates were significantly increased by the application of either phosphogypsum and magnesium chloride brine amendments. After 30 minutes of simulated rainfall, amended test plots maintained moderate (2-6 cm/hr) infiltration rates. Over the same time period, the infiltration rate on unamended spoil dropped to .1 cm/hr.

A specific effect of magnesium (hydraulic conductivity reduction) resulting from magnesium chloride brine application was not apparent.

6.4.2 Vegetation Response

Chemical amendment application resulted in germination and establishment of seeded vegetation. Unamended spoil at the research site supports very minimal vegetative cover. Total seedling density was not significantly different between phosphogypsum and magnesium chloride brine treated plots. Test plots with nitrogen fertilizer at 67 kg/ha had the greatest seedling density compared to 0 and 134 kg/ha nitrogen. Wheat straw mulch which contained viable seed heads resulted in substantial germination and establishment of annual wheat plants. The presence of this species was desirable as a quickly establishing cover crop.

Magnesium chloride brine treated plots had significantly greater plant canopy cover at 39.3%, compared to 28.6% on phosphogypsum treated plots. For both treatments, non-seeded annual forbs provided the majority of canopy cover compared to the other plant classes.

Above ground plant production of non-seeded annual forbs was greatest among plant classes for both treatments. Production of non-seeded annual forbs on phosphogypsum treated plots was 60% of total production. On magnesium chloride treated plots, non-seeded forbs contributed 83% of the total production.

Among seeded species, perennial grasses consistently produced the greatest biomass. Seeded shrubs and forbs contributed moderately to total production and were established in limited numbers across the site.

Magnesium chloride treated plots had significantly greater root biomass production than phosphogypsum treated plots. Due to the relatively short time period since plot implementation, root development was limited.

Annual pioneer species were the dominate vegetative type on reclaimed test plots over the first two growing seasons. Robust annuals are desirable sources of protection for establishing seeded species. Over time, seeded perennial species will replace the annuals and dominate the site.

One notable shortcoming of both phosphogypsum and magnesium chloride brine was their inability to promote establishment of vegetative cover during the first growing season. Dollhopf and Bauman (1981) reported similar first year vegetation performance with agricultural gypsum and calcium chloride amendments on adjacent test plots. Limited effectiveness during the first growing season appears to be a common characteristic of chemical amendments on bentonite mine spoils. Two growing seasons appear to be required for mine-soil physicochemical improvements to progress to the stage at which a stable ground cover can establish. One option may be to postpone seeding for approximately one year following amendment application. The delay would allow time for applied amendments to improve minesoil conditions.

The use of an organic amendment such as manure or wood-chips in combination with a chemical amendment is another alternative. This was the amendment scheme used by the Wyoming Department of Environmental Quality for abandoned bentonite minesite reclamation (Anselmi 1986). Organic amendments promote initial vegetative establishment, while chemical amendments induce amelioration of adverse minesoil physicochemical properties. Phosphogypsum or magnesium chloride brine would be effective and cost feasible in an organic /chemical amendment combination.

7.0 AMENDMENT COSTS FOR RECLAMATION OF ABANDONED BENTONITE MINESOILS

This chapter estimates costs of inorganic and organic minesoil amendments as well as costs for surface manipulation treatments. These costs will change as a function of time, transportation, site location and other factors, but these data should serve well to estimate reclamation costs. Note that the indicated product suppliers are not the sole source, but are only the source of the specific table information. All specifications should be reconfirmed prior to use in final project plans.

7.1 CHEMICAL AMENDMENTS

Table 42 presents cost and physical specifications for eight different chemical amendments. When reviewing costs, it should be noted whether or not the listed cost per ton of amendment includes transportation. For example, sulfuric acid in Montana may cost approximately \$5.00 per ton at the production site, but by the time it is transported to Colony, Wyoming (project site), the cost may be approximately \$80 per ton. Whether truck or railroad is selected often affects the cost significantly.

The physical state of these amendments is an important consideration. For example, CaCl_2 can be purchased bulk in liquid, flakes or pellets. The scope of work for a site reclamation plan needs to specify the source of the amendments so that the field contractor has the appropriate application equipment.

The particle size distribution and purity are critical when selecting an amendment. It has been documented that chemical amendment material more coarse than 60 mesh (>0.25 mm) may never react with the soil chemistry, meaning it is inert (Tisdale and Nelson 1966). Only when the chemical amendment is more fine than 100 mesh (<0.149 mm) does it react immediately with the soil chemistry. For example, gypsum can be purchased either 69% CaSO_4 or 85% CaSO_4 , but the 85% CaSO_4 had only 58% of the product smaller than 100 mesh, where as, the 69% CaSO_4 material was all more fine than 100 mesh, making it the superior amendment per ton of material.

7.2 ORGANIC AND SURFACE AMENDMENTS

Table 43 presents costs for woodchips, manure, straw mulch, topsoil and various surface tillage practices. Although manure proved to be a very good treatment in test plot research, it may not be feasible for large scale project areas

Table 42. Specifications for chemical amendments on bentonite mine land.

Treatment	Approximate Cost	Transporation	Application Rate (Range)	Purity	Solubility in H ₂ O(g/L)	Physical Nature	Size	Potential Distributors	References
H ₂ SO ₄ (Sulfuric Acid)	\$80/ton	FOB Colony, WY	5-15 ton/acre	93-98%	----	Liquid	---	Western Nuclear, Riverton, WY Chemical Sales Co., Denver, CO Dyco Chemical, Billings, MT ASARCO, Helena, MT	Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985
Phosphogypsum	\$40-60/ton	FOB Colony, WY	5-20 ton/acre	93-5%	25	Powder	87% <100 Mesh 65% <200 Mesh	J.R. Simplot, Pocatello, ID	D.J. Dollhopf, 1986
	\$70/ton	FOB Colony, WY		N/A ¹	25	Powder	N/A	Chevron Corp., Magna, Utah	Range Inventory and Analysis, 1986 Ron Schreibeis, 1987
CaSO ₄ (Gypsum) CaSO ₄ ·2H ₂ O CaSO ₄ ·2H ₂ O	\$75/ton (sacks) \$55/ton (bulk)	FOB Colony, WY FOB Colony, WY	5-20 ton/acre	69% 69%	2.4 @ 20°C 2.4 @ 20°C	Powder Powder	100% <100 Mesh 100% <100 Mesh	U.S. Gypsum, Heath, MT U.S. Gypsum, Heath, MT Dyco Chemical, Billings, MT WYO-BEN, Billings, MT U.S. Gypsum, Des Plaines, IL	Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985
CaSO ₄ ·2H ₂ O	\$30/ton (bulk)	FOB Colony, WY		85%	2.4 @ 25°C	Variable	58% <100 Mesh	Hills Materials, Rapid City, SD	DK Resources, 1987
CaCl ₂ CaCl ₂ CaCl ₂ ·2H ₂ O CaCl ₂ ·2H ₂ O CaCl ₂ ·2H ₂ O CaCl ₂	\$350/ton (sacks) \$230/ton (bulk) \$250-300/ton N/A \$300/ton	@ Billings FOB Colony, WY FOB Colony, WY N/A FOB Colony, WY	5-15 ton/acre	94-97% 77-80% 94-97% 30-42%, 45% 94-97%	745 @ 20°C 977 @ 0°C 977 @ 0°C --- 745 @ 20°C 977 @ 20°C	Pellets Flake Liquid Liquid Pellets Pellets Flakes	>80% < No. 4 Sieve >80% < No. 4 Sieve Recrystallized Diluted Flake 80% No. 4 Sieve >80% < No. 4 Sieve >80% < No. 4 Sieve	Dyco Chemical, Billings, MT Chemical Sales Co., Denver, CO Artesian Chemical Co., Denver, CO Dow Chemical, Midland, MI Dow Chemical, Midland, Michigan Dow Chemical, Midland, MI Dow Chemical, Midland, MI	Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 DK Resources, 1987 OK Resources, 1987 Karen Thompson, Dow Chemical, 1987 Karen Thompson, Dow Chemical, 1987 Karen Thompson, Dow Chemical, 1987
CaCl ₂ CaCl ₂ CaCl ₂ ·2H ₂ O	\$228/ton (bulk) \$150/ton (bulk)	Not included Not included		>90% 77-80%					
	\$78.00/ton FOB Billings								
MgCl ₂	\$50-75/ton	FOB Colony, WY	5-30 ton/acre	32%	---	Liquid Brine	---	Dyco Chemical, Billings, MT Artesian Chemical Co., Denver, CO Great Salt Lake Mineral & Chemical Ogden, Utah	Dollhopf and Jensen, 1985 Dollhopf and Jensen, 1985 Gene Hanson, 1987 Gene Hanson, 1987
MgCl ₂ ·6H ₂ O	\$40/ton \$250/ton (sacks)	Not included Not included		32% 47%	1167 @ 20°C	Liquid Brine Flake	>80% < No. 4 Sieve		
CaCO ₃	\$78-100/ton (sacks) \$10/ton (bulk)	@ Billings, MT. FOB Rapid City 3.10/ton mile	5-30 ton/acre	>90% >92%	.014 @ 25°C .014 @ 25°C	Powder Powder	50% < 100 Mesh 99% < 100 Mesh 87% < 200 Mesh	Dyco Chemical, Billings, MT Hills Materials, Rapid City, SD	Mark Redfern, Dyce Chemical, 1986 Dan Michael, Hills Materials, 1987
CaCO ₃	\$85/ton	FOB Colony, WY		92%		Powder	99% 100 Mesh 87% 200 Mesh	Hills Materials, Rapid City, S.O.	DK Resources, 1987
Ca·MgCO ₃ (dolomitic lime)	\$115-120/ton (sacks)	FOB Billings MT	5-30 ton/acre	>90%	.078 @ 18°C	Powder	50% < 100 Mesh	Jirdon Chemical Co., Morrill, NB	Lloyd Dunn, Jirdon Chemical, 1986
CaO Cement plant Flue Dust Sugar Beet Tailings Fly Ash	\$10/ton Loading and freight Loading and freight @ Colstrip, MT	Not included Not included @ Colstrip, MT	5-30 ton/acre 5-30 ton/acre 5-30 ton/acre	49% 85% 15-40%	1.31 @ 10°C 1.31 @ 10°C 1.31 @ 10°C	Powder Powder Powder	70% < 200 Mesh 92% < 100 Mesh N/A Fine silt-silt	Cement plants Requires development Western Energy, Colstrip, MT	Gary Huls, Ideal Cement, 1987

¹ N/A represents data not currently available

Table 43. Specifications for physical amendments on bentonite mine land.

Treatment	Approximate Costs	Distributors	Equipment	Comments	Source
Deep Chisel Plowing	\$75/acre (18" depth) \$22/acre	Contractor Contractor	Tractor with chisel tool bar	Price based on bid price in Wyo AML Project 12-A Average bid price Wyo AML Project 11, IMEC. Range \$10-30/ac	Schuman and Johnson, 1985 Kurt Anselmi, 1987
Woodchips or Wood Residue	\$19/ton (dry wt., delivered) \$0-5/ton (at millsite) \$3.25/Cu. yd. (8 cu.yd./1 ton varies w/H ₂ O content)	Local sawmills Local sawmills Contractor	Front end loader and manure spreader Tractor and manure spreader	This cost represents the average cost in a Wyo Pilot Project (AML-12A). Many mills are under contract with paper mills or Wyo DEQ for woodchips making the supply limited Price includes material, transportation, equipment use, and operator at 132 cu.yd/acre rate	Schuman and Johnson, 1985 Harza Engineering Co, 1985 DK Resources, 1987
Nitrogen fertilizer (in combination with wood residue)	\$600/ton	Contractor	Tractor and fertilizer spreader	Applied at approximately .5 ton/acre depending upon wood residue application rate.	DK Resources, 1987
Straw Mulch	\$240/acre (@ 2 ton/acre includes crimping) \$162/acre	Local Ranches or Contractor Contractor	Tractor/manure spreader/crimper or coulter disc	Supply and price will vary with annual hay crop success. Apparently includes straw, equipment, and operator. Average bid price. Harza	Harza Engineering Co, 1985 Kurt Anselmi, 1987
Topsoil	\$500-1200/acre (6" depth)	Contractor	Scraper or dozer	Prices based on varying haul distance less than 1/3 mi. Supply depends on suitable borrow material adjacent to project areas.	Harza Engineering Co, 1985
Topsoil (salvage/replace)	\$.75/cu. yd. \$.95/cu. yd.	Contractor Contractor	Scraper or dozer Scraper or dozer	Average bid price for Wyoming AML-11. IMEC Average bid price for Wyoming AML-12. Chen.	Kurt Anselmi, 1987 Kurt Anselmi, 1987

Table 43. Continued.

Deep Ripping (to 3 foot depth w/10 ft spacing)	\$100-130/acre \$82/acre	Contractor Contractor	Dozer Dozer	Apparently includes equipment use and operator Apparently includes equipment use and operator. Average bid price for Wyo. AML-11, Harza. Range of \$40-200/acre.	Harza Engineering Co, 1985 Kurt Anselmi, 1987
Shallow Ripping (to 20 in. depth 0/18 ft spacing)	\$36/acre \$78/acre	Contractor Contractor	Tractor/Dozer Tractor/Dozer	Apparently includes equipment use and operator. Apparently includes equipment use and operator. Average bid price for Wyo. AML-11, Harza. Range of \$50-100/acre.	Harza Engineering Co, 1985 Kurt Anselmi, 1987
Disking (for amendment incorporation)	\$16/acre (6"depth) \$32/acre (12"depth) \$30/acre (8"depth)	Contractor	Tractor and Disc Tractor and Disc	Apparently includes equipment use and operator. Includes equipment use and operator. Used to incorporate chemical and organic amendments.	Harza Engineering Co, 1985 DK Resources, 1987
Manure @50-200 ton/ acre	Loading and tran- sportation costs only	Local feedlots	Loader/Manure Spreader	Probably not a feasible alternative for large scale projects. No known large scale suppliers in the area.	
Pitting	\$85/acre	Contractor Dammer-Diker distributed by AG Engineering and Development Co.	Tractor and Dammer- Diker implement.	Includes equipment use and operator	DK Resources, 1987
	\$121/acre	Contractor	Tractor and mech- anical implement.	Average bid price Wyo AML-11. Harza.	Kurt Anselmi, 1987
Gouge	\$45/acre	Contractor	Tractor and Hodder gouger implement.	Includes equipment use and operator	Bernie Jenson, 1987
Fence	1.04/linear ft.	Contractor		4 barb fence installed, average bid, Wyo AML-IMEC.	Kurt Anselmi, 1987
	1.54/linear ft.	Contractor		3 barb fence installed, average bid, Wyoming AML-11, Harza.	Kurt Anselmi, 1987

due to the great tonnages required and relatively small supply located nearby. As site project plans develop, it may become apparent that neither manure nor woodchips will be available in sufficient quantities. In order to control erosion during the early years of reclamation, some sort of surface pitting (gouging, dammer-diker) should be used with or without organic amendments. Ripping on the contour may not be adequate.

Lastly, Table 44 presents seeding costs and the seed mix used on abandoned bentonite minesoils in Wyoming. The most common group of plants being used were the native wheatgrasses. These species have proven themselves adapted to the regional climate and soils and are relatively inexpensive and easy to seed. Since the reclamation process on these abandoned minelands is not under any legal constraints to seed native species, adapted introduced species are also being used.

Table 44. Seed mixture specifications for bentonite mine land.

Treatment	Approximate Cost	Total PLS/Acre	Seed Mix	PLS/Acre	Comments	Reference	
Seeding	\$195/acre	29.25 lbs	Slender wheatgrass (Agropyron trachycaulum) var. Revenue	4 lbs.	Seeding is by drill method with possible exceptions on service areas which may be broadcast seeded and covered. Price includes seed, equipment use, and operator.	IMEC, 1986	
			Thickspike wheatgrass (A. dasystachyum) var. Critana	5 lbs.			
			Western wheatgrass (A. smithii) var. Rosana	5 lbs.			
			Streambank wheatgrass (A. riparium) var. Sodar	4 lbs.			
			Intermediate wheatgrass (A. intermedium) var. Tegmar	4 lbs.			
			Russian wildrye (Elymus junceus) var. Vinall	4 lbs.			
			Four-Wing saltbush (Atriplex canescens) var. Standard	1 lbs.			
			Rubber rabbitbrush (Chrysothamnus nauseosus)	.25 lbs.			
			Yellow sweetclover (Melilotus officinalis) var. Madrid	2 lbs.			
Seeding	\$185/acre		This unit cost reflects the average bid price for seeding received by Harza Engineering for Wyoming AML project areas. Bids ranged from \$140-400/acre including seed, equipment use, and operator. Four possible seed mixes are given.			Kurt Anselmi, Wyo. DEQ, 1987	
(Mix #1)	12.10 lbs		Western wheatgrass (Agropyron smithii) var. Rosana	3.1 lbs.	To be drill seeded on upland sites which have been topsoiled or have Mowry Shale or mixed Belle Fourche/Mowry Shales exposed.	Harza Engineering Co., 1986	
			Streambank wheatgrass (A. riparium) var. Sodar	1.6 lbs.			
			Slender wheatgrass (A. trachycaulum) var. Revenue	1.3 lbs.			
			Russian wildrye (Elymus junceus) var. Vinall	1.0 lbs.			
			Green needlegrass (Stipa viridula) var. Lodorm	1.1 lbs.			
			Indian ricegrass (Oryzopsis hymenoides) var. Nezpar	1.1 lbs.			
			Prairie sandreed (Calamovilfa longifolia) var. Goshen	.63 lbs.			
			Yellow sweetclover (Melilotus officinalis)	.5 lbs.			
			Four-Wing saltbush (Atriplex canescens)	1.66 lbs.			
			Rubber rabbitbrush (Chrysothamnus nauseosus)	.11 lbs.			
(Mix #2)	17.38 lbs		Western wheatgrass (Agropyron smithii) var. Rosana	3.0 lbs.	Used for broadcast seeding over drainageways which have been topsoiled or drainages with Mowry Shale or mixed Belle Fourche/Mowry Shales.	Harza Engineering Co., 1986	
			Streambank wheatgrass (A. riparium) var. Sodar	.16 lbs.			
			Slender wheatgrass (A. trachycaulum) var. Revenue	1.28 lbs.			
			Russian wildrye (Elymus junceus) var. Vinall	1.02 lbs.			
			Green needlegrass (Stipa viridula) var. Lodorm	1.0 lbs.			
			Indian ricegrass (Oryzopsis hymenoides) var. Nezpar	1.07 lbs.			
			Prairie sandreed (Calamovilfa longifolia) var. Goshen	.63 lbs.			
			Tall wheatgrass (Agropyron elongatum) var. Alkar	3.6 lbs.			
			Greatbasin wildrye (Elymus cinereus) var. Magnar	1.72 lbs.			
			Nuttalls alkaligrass (Puccinella nuttallii)	.22 lbs.			
Canada bluegrass (Poa compressa)	.04 lbs.						
Yellow sweetclover (Melilotus officinalis)	.5 lbs.						
Four-Wing saltbush (Atriplex canescens)	.83 lbs.						
Rubber rabbitbrush (Chrysothamnus nauseosus)	.11 lbs.						
Winterfat (Ceratoide lanata)	.76 lbs.						

Table 44. Continued.

(Mix #3)	11.97 lbs	Western wheatgrass (Agropyron smithii) var. Rosana Streambank wheatgrass (A. riparium) var. Sodar Slender wheatgrass (A. trachycaulum) var. Revenue Russian wildrye (Elymus junceus) var. Vinal Green needlegrass (Stipa viridula) var. Lodorm Sheep fescue (Festuca ovina) var. Covar Yellow sweetclover (Melilotus officinalis) Four-Wing saltbush (Atriplex canescens) Gardner saltbush (A. gardneri) Rubber rabbitbrush (Chrysothamnus nauseosus)	3.1 lbs. 1.86 lbs. 1.3 lbs. 1.0 lbs. 1.38 lbs. .26 lbs. .50 lbs. 1.66 lbs. .80 lbs. .11 lbs	To be drill seeded on upland areas which have Belle Fourche Shale on the surface.	Harza Engineering Co., 1986	
(Mix #4)	15.42 lbs	Western wheatgrass (Agropyron smithii) var. Rosana Streambank wheatgrass (A. riparium) var. Sodar Slender wheatgrass (A. trachycaulum) var. Revenue Russian wildrye (Elymus junceus) var. Vinal Green needlegrass (Stipa viridula) var. Lodorm Sheep fescue (Festuca ovina) var. Covar Tail wheatgrass (Agropyron elongatum) var. Alkar Greatbasin wildrye (Elymus cinereus) var. Magnar Nuttals alkaligrass (Puccinella nuttallii) Smooth brome (Bromus inermis) var. Manchac Yellow sweetclover (Melilotus officinalis) Four-Wing saltbush (Atriplex canescens) Gardner saltbush (A. gardneri) Rubber rabbitbrush (Chrysothamnus nauseosus)	3.0 lbs. 1.85 lbs. 1.28 lbs. 1.02 lbs. 1.32 lbs. .25 lbs. 1.8 lbs .86 lbs .22 lbs .75 lbs. .50 lbs. 1.66 lbs. .80 lbs. .11 lbs	Used for broadcast seeding over drainageways which have exposed Belle Fourche Shale on the surface.	Harza Engineering Co., 1986	
Seeding	N/A	15.0 lbs	Western wheatgrass (Agropyron smithii) var. Rosana Slender wheatgrass (A. trachycaulum) var. Revenue Thickspike wheatgrass (A. dasystachyum) var. Critana Four-Wing saltbush (Atriplex canescens) Yellow sweetclover (Melilotus officinalis) var. Madrid	5.0 lbs. 5.0 lbs. 4.0 lbs. .5 lbs. .5 lbs.	Drill seeding method at .5 inch depth.	Chen and Associates, 1986

8.0 LITERATURE CITED

- Agricultural Research Service. 1977. North Dakota progress report on research on reclamation of strip-mined lands - update 1977. U.S. Dept. Agr. ARS and ND Agr. Exp. Sta., Mandan and Fargo, ND. 26 p.
- Ampian, S.G. 1985. Clays In: Mineral Facts and Problems. U.S. Bureau of Mines, Bull. 675. Washington, D.C. pp. 157-169.
- Anselmi, K.M. 1986. Ameliorating the adverse chemical and physical properties of bentonitic clays In: Proc. of the 8th Ann. Nat. Abandoned Mine Lands Conf. Billings, MT. pp. 204-209.
- Anselmi, K.M. 1987. Personal communication. Bidding spread sheets for Wyoming AML bentonite reclamation. Wyoming DEQ, Cheyenne, WY.
- Arora, H.S. and N.T. Coleman. 1979. The influence of electrolyte concentrations on flocculation of clay suspensions. Soil Sci., V. 127, No. 3. pp. 134-139.
- Berg, R.B. 1969. Bentonite in Montana. Montana Bureau of Mines and Geology, Montana College of Mineral Science and Technology, Butte, MT, Bull. 74.
- Bjugstad, A.J. 1979. Bentonite mine spoil and pit reclamation - major problem In: Proc. of Mineral Waste Stabilization Liasion Committee, Erie Mining Co., Eveleth, MN. 21 p.
- Bjugstad, T. Yamamotat and D.W. Uresk. 1981. Shrub establishment on coal and bentonite clay minesoils In: Proc. of Shrub Establishment. Univ. of Wyoming, Laramie, WY.
- Bohn, H.L., B.L. McNeal and G.A. O'Connor. 1985. Soil Chemistry, 2nd edition. John Wiley and Sons, New York, NY. 341 p.
- Buckman, H.O. and N.C. Brady. 1969. The Nature and Properties of Soils, 7th edition. The Macmillan Co., New York, NY. 653 p.
- Byrne, P.J. and R.N. Farvolden. 1959. The clay mineralogy of the Bearpaw Formation of Southern Alberta. Research Council Alberta. Bull. No. 4., 44 p.

- Chen and Associates, Inc., Range Inventory and Analysis; Worthington, Lenhart, Carpenter and Johnson, Inc. 1986. Contract documents, plans and specifications for Wyoming AML project 12, sites 12-45. Casper, WY.
- Chow, Harbaugh.
- Climatological data. National Oceanic and Atmospheric Administration. National Climatic Data Center, Asheville, NC.
- Daubenmire, R. 1959. A canopy coverage method of vegetational analysis. Northwest Sci. 33:43-64.
- Daubenmire, R. 1968. Plant Communities: A Textbook of Plant Synecology. Harper and Row, New York, NY.
- Day, P.R. 1965. Particle fractionation and particle size analysis In: Methods of Soil Analysis. C.A. Black (ed.). Amer. Soc. of Agron. Mono. No. 9, Part 2. Madison, WI. pp. 545-567.
- Dengo, G.O. 1946. Geology of bentonite deposits near Casper, Natrona County, Wyoming. Geol. Surv. of WY., Bull. No. 37. Univ. of Wyoming, Laramie, WY. pp. 7-8.
- DK Resources, Inc. 1987. Reclamation of bentonite spoils in Crook County, Wyoming - costs and specifications. Lander, WY.
- Dollhopf, D.J. 1975. Soil and water relationships with gypsum and land disposed feedlot wastes. Ph.D. Thesis. Montana State University, Bozeman, MT.
- Dollhopf, D.J., E.J. DePuit and M.G. Klages. 1980. Chemical amendment and irrigation effects on sodium migration and vegetation characteristics in sodic minesoils in Montana. MT Agr. Exp. Sta., Bull. 736. Montana State Univ., Bozeman, MT. 109 p.
- Dollhopf, D.J. and B.J. Bauman. 1981. Bentonite mine land reclamation in the Northern Great Plains. MT Agr. Exp. Sta., Resch. Rep. 179. Montana State Univ., Bozeman, MT. 42 p.
- Dollhopf, D.J. and I.B. Jensen. 1985. Recommended abandoned bentonite reclamation procedures for northeast Wyoming. Technical report to IMEL (Intermountain Mineral and Energy Consultants, Inc.), Sundance, WY.

- Dollhopf, D.J., R.C. Postle, R.B. Rennick and S.A. Young. 1985. Chemical amendment and irrigation effects on sodium migration and vegetation characteristics in 7-year old sodic minesoils. MT Agr. Exp. Sta., Resch. Rep. SR-17. Montana State Univ., Bozeman, MT. 109 p.
- Dollhopf, D.J. 1986. Technical report to IMEL concerning the use of phosphogypsum as a bentonite spoil amendment.
- Dollhopf, D.J., J.D. Goering and R.C. Postle. 1988. Minesoil topsoil sodication rates at the Decker Mine in Montana. Submitted to the Journal of Environmental Quality. In Review. Montana State Univ., Bozeman, MT.
- Dunn, L. 1986. Personal communication. Jirdon Chemical Company, Morrill, NE.
- EPA. 1982. Test methods for evaluating solid waste, physical and chemical methods, 2nd edition. U.S. Environmental Protection Agency. Office of Solid Waste and Emergency Response, Washington, D.C. SW-846.
- EPA. 1987a. Assessment of toxicity of arsenic, cadmium, lead and zinc in soil, plants, and livestock in the Helena Valley of Montana. U.S. Environmental Protection Agency. Contract No. 68-01-7251. Denver, CO. 206 p.
- EPA. 1987b. Assessment of the toxicity of copper, mercury, selenium, silver and thallium in soil and plants in the Helena Valley of Montana. U.S. Environmental Protection Agency. Contract No. 68-01-7251. Denver, CO. 88 p.
- EPA. 1987c. Contract laboratory program - statement of work for inorganic analysis, multi-media, multi-concentration. SOW No. 787, Washington, DC.
- Fitts, J.W., E.S. Lyons and H.F. Rhoades. 1943. Chemical treatment of slick spots. Soil Sci. Soc. Am. Proc. 8:432-436.
- Gal, M., L. Arian, I. Shainberg and R. Keren. 1984. Effect of exchangeable sodium and phosphogypsum on crust structure-scanning electron microscope observations. Soil Sci. Soc. Am. J. 48:872-878.
- Gardner, W.H. 1986. Water content In: Methods of Soil Analysis, Physical and Mineralogical Methods. C.A. Black (ed.). Agron. Mono. No. 9, Part 1. pp. 493-544.

- Gould, W.L. 1978. Approach to reclamation of surface mined land in the fruitland formation in New Mexico In: Ecology and Coal Resource Development. M.K. Wali (ed.). Pergamon Press, pp. 850-858.
- Grim, R.E. 1968. Clay Mineralogy, 2nd edition. McGraw-Hill Book Co., New York, NY. 596 p.
- Hanson, G. 1987. Personal communication. Great Salt Lake Mineral and Chemical Co., Ogden, UT.
- Harza Engineering Co. 1985. Reclamation approaches and techniques for sodic, low pH spoil in abandoned bentonite mines. A technical report submitted to Wyoming DEQ, Denver, CO.
- Hemmer, D., S. Johnson and R. Beck. 1977. Bentonite mining related problems in the northwestern states. Montana Department State Lands Report to Old West Regional Commission, Billings, MT. 94 p.
- Hemmer, D., S. Johnson and R. Beck. 1977. Bentonite mining related reclamation problems. Old West Regional Commission Report. Montana Department of State Lands, Helena, MT.
- Hewett, D.F. 1917. The origin of bentonite and the geologic range of related materials in the Big Horn Basin, Wyoming. J. Washington Academy of Sci. 7:196-198.
- Hillel, D. 1980. Fundamentals of Soil Physics. Academic Press, New York, NY. 364 p.
- Huls, G. 1987. Personal communication. Ideal Cement Co., Trident, MT.
- Hunter, A.S. 1949. Yield and composition of alfalfa as affected by variations in the calcium:magnesium ratio in the soil. Soil Sci. 67:53-62.
- Intermountain Mineral and Energy Consultants, Inc. 1986. Contract documents for reclamation of abandoned mines, AML-11, sites 41, 42, 45, and 46; Crook County, Wyoming. Lander, WY.
- Jensen, I.B. 1987. Personal communication. Western Reclamation. Bozeman, MT.
- Kabata-Pendias, A. 1979. Current problems in chemical degradation of soils. Paper presented at Conf. on Soil and Plant Analysis in Environmental Protection. Falenty/Warsaw, October 29. 7 (Po).

- Kabata-Pendias, A. and H. Pendias. 1984. Trace Elements in Soils and Plants. CRC Press, Boca Raton, FL. 315 p.
- Kazman, Z., I. Shainberg and M. Gal. 1983. Effect of low levels of exchangeable sodium and applied phosphogypsum on the infiltration rate of various soils. Soil Sci. V. 135, No. 3., pp. 184-192.
- Keren, R. and I. Shainberg. 1981. Efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. Soil Sci. Soc. Am. J. 45:103-107.
- Klages, M.G. and R.W. Hopper. 1982. Clay minerals in Northern Plains coal overburden as measured by x-ray diffraction. Soil Sci. Soc. Am. J. 46:415-419.
- Knechtel, M.M. and S.H. Patterson. 1956. Bentonite deposits in marine Cretaceous formations, Hardin district, Montana and Wyoming. U.S. Geol. Surv. Bull. 1023., 116 p.
- Knechtel, M.M. and S.H. Patterson. 1962. Bentonite deposits of the Northern Black Hills district, Wyoming, Montana and South Dakota. U.S. Geol. Surv. Bull. 1082-M. pp. 893-1030.
- Kovalskiy, V.V. 1974. Geochemical environment, health and diseases In: Trace Subst. Environ. Health, D.D. Hemphill (ed.) V. 8. Univ. of Missouri, Columbia, MO.
- LeClerc, E.L., W.H. Leonard and A.G. Clark. 1962. Field Plot Technique. Burgess Publishing Co., Minneapolis, MN. pp. 338-351.
- Lindsay, W.L. 1979. Chemical equilibria in soils. See diagram, p. 94 and associated text. John Wiley and Sons, New York.
- Meeuwig, R.O. 1971. Infiltration and water repellency in granitic soils. Intermountain Forest and Range Exp. Sta. Resch. Paper INT-111. Ogden, UT. 20 p.
- Merrill, S.D., F.M. Sandoval, J.F. Power and E.J. Doering. 1980. Salinity and sodicity factors affecting suitability of materials for mined land reclamation In: Adequate Reclamation of Mined Lands. Symposium Proc. p. 3-1 - 3-25. Soil Conser. Soc. of Am. Billings, MT.
- Michael, D. 1987. Personal communication. Hills Materials Co., Rapid City, SD.

- Montana Department of State Lands. 1983. Soil and Overburden Guidelines. Reclamation Division, Coal/Uranium Bureau. Helena, MT.
- National Academy of Science/National Academy of Engineering. 1973. Rehabilitation potential of western coal lands. Report to the Energy Policy Project of the Ford Found. Washington, DC. 206 p.
- NOAA. 1986. National Oceanic and Atmospheric Admin. Climatological Data, Annual Summary for South Dakota. National Climatic Center, Asheville, NC., V. 91, No. 13.
- NOAA. 1987. National Oceanic and Atmospheric Admin. Climatological data. National Climatic Center, Asheville, NC., V. 92, No.'s 1-6.
- Overstreet, R., J.C. Martin and M.H. King. 1951. Gypsum, sulfur, and sulfuric acid for reclaiming an alkali soil of the Fresno series. Hilgardia 21:113-126.
- Padhi, U.C., R.T. Odell, J.B. Fehrenbacher and R.D. Sief. 1965. Effect of gypsum and starch on water movement and sodium removal from solonetic soils in Illinois. Soil Sci. Soc. Am. Proc. 29:227-229.
- Pair, C.H. and G.C. Lewis. 1959. Chemical and intake rate changes with various treatments on Sebree-Chilcott soil series association (slick spots). Soil Sci. 79:234-238.
- Papinyan, V.A. 1980. Effect of magnesium chloride on the physical and chemical properties of sodic solonetz-solonchaks of the Ararat Plain. Tr. NII Pochvoved. Asrokhimii. ARM552, No. 15., pp. 170-174.
- Petersen, L. and R.N. Oad. 1974. Alkali soil reclamation with concentrated solutions. Asian Institute Tech., Bangkok, Thailand. Thai J. Agr. Sci., V. 7, No. 3. pp. 145-159.
- Power, J.R., R.W. Ries and F.M. Sandoval. 1976. Use of soil materials on spoils - Effect of thickness and quality. North Dakota Farm Resch. 34(1):23-24.
- Prather, R.J., J.O. Goertzen, J.D. Rhoades and H. Frenkel. 1978. Efficient amendment use in sodic soil reclamation. Soil Sci. Soc. Am. J., V. 42:782-786.
- Quirk, J.P. and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci., V. 6, No. 2., pp. 163-178.

- Rahman, W.A. and D.L. Rowell. 1979. The influence of magnesium in saline and sodic soils: a specific effect or a problem of cation exchange? J. Soil Sci., 30:535-546.
- Range Inventory and Analysis. 1986. Radium 226 concentration study of two phosphogypsum sources on Belle Fourche and Mowry shales in northeastern Wyoming. Tech. Rep. prepared for Wyoming DEQ - AML 12. Laramie, WY. (Unpublished Report).
- Redfern, M. 1986. Personal communication. Dyce Chemical and Engineering, Billings, MT.
- Regis, A.J. 1978. Correlation between physical properties and exchangeable chemistry of bentonites from the Western United States. U.S. Dept. of Int. BLM Tech. Note 313. 56 p.
- Richards, L.A. 1953. Modulus of rupture as an index of crusting soil. Soil Sci. Soc. Am. Proc. 17:321-323.
- Richards, L.A. 1969. Diagnosis and improvement of saline and alkali soils. USDA Agri. Handbook No. 60, Washington, DC.
- Romo, J. 1981. Bentonite: clay of 1000 uses. Western Wildlands. 7:32-36.
- Rowell, D.L. and I. Shainberg. 1979. The influence of magnesium and of easily weathered minerals on hydraulic conductivity changes in a sodic soil. J. Soil Sci. 30: 719-726.
- Sandoval, F.M., J.J. Bond, J.F. Power and W.O. Willis. 1973. Lignite mine spoils in the Northern Great Plains - characteristics and potential for reclamation In: Some Environmental Aspects of Strip Mining in North Dakota, ND Geol. Surv., Educ. Ser. 5, Grand Forks, ND. pp. 1-24.
- Sandoval, F.M. and W.L. Gould. 1978. Improvement of saline and sodium affected disturbed lands In: Reclamation of Drastically Disturbed Lands. Pub. by Amer. Soc. Agron., Madison, WI. pp. 485-502.
- Schachtshabel, P. 1940. Kolloid-Beih 51:199-276.
- Schreibeis, R. 1987. Personal communication. Range Inventory and Analysis, Laramie, WY.
- Schuman, G.E. and T.A. Sedbrook. 1984. Sawmill wood residue for reclaiming bentonite spoils. For. Prod. J. 34:65-68.

- Schuman, G.E. and Johnson, C. 1985. Economic analysis of wood residue reclamation of bentonite mine spoils. Wyoming DEQ - AML 12-A.
- Schuurman, J.J. and M.A.J. Goedewaagen. 1971. Methods for the Examination of Root Systems and Roots. Centre for Agricultural Publishing and Documentation, Wageningen, Germany. pp. 16, 32.
- Shacklette, H.T. and J.G. Boerngen. 1984. Element concentrations in soils and other surficial materials of the conterminous United States. U.S. Geol. Surv. Prof. Paper, 1270.
- Sieg, C.H., D.W. Uresk and R.M. Hansen. 1982. The biological costs of not reclaiming bentonite mine spoils In: Proc. of the Ann. Conf. of the Western Assn. of Fish and Wildlife Agencies, July 18-22, 1982. Las Vegas, NV. pp. 2-72-277.
- Sieg, C.H., D.W. Uresk and R.M. Hansen. 1983. Plant-soil relationships on bentonite mine spoils and sagebrush-grassland in the northern high plains. J. of Range Mgmt., V. 36, No. 2. pp. 289-294.
- Simson, C.R., R.B. Corey and M.E. Sumner. 1979. Effect of varying Ca:Mg ratios on yield and composition of corn (Zea mays) and alfalfa (Medicago sativa). Commun. Soil Sci. Plant Anal. 10:153-162.
- Smith, I.C. and B.L. Carson. 1977a. Trace Metals in the Environment, V. 2. Ann Arbor Scientific Publications. Ann Arbor, MI. 469 p.
- Smith, I.C. and B.L. Carson. 1977b. Trace Metals in the Environment, V. 1. Ann Arbor Scientific Publications. Ann Arbor, MI. 394 p.
- Smith, J.A., G.E. Schuman, E.J. Schuman and T.A Sedbrook. 1985. Wood residue and fertilizer amendment of bentonite spoils: I. Spoil and general vegetation responses. J. Environ. Qual. 14:575-580.
- Smith, J.A., E.J. DePuit and G.E. Schuman. 1986. Wood residue and fertilizer amendment on bentonite mine spoils: II. Plant species responses. J. Environ. Qual 15:427-435.
- Soil Conservation Service. 1951. Soil Conservation Service Staff. Soil Survey Manual. USDA Agricultural Handbook No. 18. Washington, DC. 503 p.

- Soil Conservation Service. 1983. National soils handbook. Part 603, USDA, Washington, DC.
- Thompson, K. 1987. Personal communication. Dow Chemical Co., Denver, CO and Midland, MI.
- Thorson, T. 1976. Bentonite mining near Kaycee, Wyoming. WY Geol. Assn. Guidebook of 1976. pp. 253-256.
- Tidball, R.R. and R.C. Severson. 1975. Geochemical reconnaissance of soils in the Northern Great Plains In: Geochemical Survey of the Western Coal Regions. U.S. Geol. Surv. Open-file Report 75-436. Denver, CO. 132 p.
- Tisdale, S.L. and W.L. Nelson. 1966. Soil Fertility and Fertilizers. The MacMillan Company, USA. 694 p. (see p 431).
- United States Department of Agriculture. 1954. Diagnosis and improvement of saline and alkali soils. Agricultural Handbook No. 60, L.A. Richards (ed.), Washington, DC.
- Uresk, D.W. and T. Yamamoto. 1986. Growth of forbs, shrubs, and trees on bentonite mine spoil under greenhouse conditions. J. of Range Mgmt., V. 39, No. 2. pp. 113-117.
- Van Schack, J.C. 1967. Influence of adsorbed sodium and gypsum content on permeability of glacial till soils. J. of Soil Sci. 18:42-46.
- Voorhees, M.E. 1986. Infiltration rate of bentonite mine spoil as affected by amendments of gypsum, sawdust and inorganic fertilizer. Reclamation and Revegetation Resch., 5:483-490.
- Weast, R.C., Astle, M.J. and W.H. Beyer (eds.). 1985. CRS Handbook of Chemistry and Physics, 66th edition. CRC Press, Inc., Boca Raton, FL. B-81-11.
- Weast, R.C. 1986. CRC Handbook of Chemistry and Physics, 67th edition. CRC Press, Boca Raton, FL. B-68-146.
- White, W.A. and E. Pilcher. 1959. Water-sorption characteristics of clay minerals. Illinois State Geol. Surv. Circ. 266. 20 p.
- White, E.M. and J.K. Lewis. 1969. Ecological effect of a clay soil's structure on some native grass roots. J. Range Mgmt. 22:401-404.

- Whittig, L.D. 1965. X-ray diffraction techniques for mineral identification and mineralogical composition In: Methods of Soil Analysis, Part 2. C.A. Black (ed.). Agron. Mono. 9, Am. Soc. of Agron., Madison, WI.
- Wolfbauer, C.A. 1976. Bentonite in the Powder River Basin, Wyoming. WY Geol. Assn. Guidebook of 1976. pp. 257-259.
- Young, S.A. and R.B. Rennick. 1982. Establishment of seeded species on coal surface minesoils following temporary irrigation. MT Agr. Exp. Sta., Resch. Rep. 200, Montana State Univ., Bozeman, MT.

9.0 APPENDICES

APPENDIX A
Plant Performance Data

Table 45. Mean¹ aboveground production (kg/ha) by plant class and treatment, June 1986, Belle Fourche, SD.

Experimental Treatment	Perennial Grasses	Annual Grasses	Forbs	Shrubs	Total Vegetation
No straw mulch	230 cd ²	14 b	228 b	0 a	472 d
Control	360 cd	6 b	50 b	0 a	416 d
Emergence irrigation	328 cd	38 b	36 b	0 a	402 d
Gouge	291 cd	31 b	72 b	0 a	394 d
Manure vertical mulch	1819 ab	66 b	961 a	5 a	2851 ab
Manure only	1987 ab	523 a	64 b	0 a	2574 ab
Manure + H ₂ SO ₄	3078 ab	30 b	61 b	0 a	3169 a
Woodchips	1574 bc	11 b	15 b	0 a	1600 bed
Gypsum + CaCl ₂	2012 ab	129 b	11 b	0 a	2152 abc
Gypsum + H ₂ SO ₄	2404 ab	80 b	13 b	0 a	2497 ab
Gypsum + H ₂ SO ₄ + irrigation	1874 ab	38 b	24 b	0 a	1936 abc
Topsoil only	648 cd	176 b	229 b	0 a	1053 cd
Topsoil + irrigation	394 cd	713 b	70 b	16 a	653 d

¹ Mean of three replications

² Means within the plant class are significantly ($P \leq .05$) different if followed by a different letter.

Table 46. Mean percent canopy coverage by plant class and treatment, June 1986, Belle Fourche, SD.

Experimental Treatment	Perennial Grasses	Annual Grasses	Forbs	Shrubs	Total Vegetation	Organic Litter	Bare Ground
No straw mulch	6.9 d ²	<0.1 c	10.6 b	0.0 a	17.5 c	1.9 c	93.1 a
Control	14.4 d	0.3 c	4.3 bc	0.0 a	19.0 c	2.6 c	92.4 a
Emergence irrigation	17.5 cd	1.1 c	1.2 c	0.0 a	19.8 c	3.2 bc	91.8 ab
Gouge	16.7 cd	0.9 c	5.0 bc	0.0 a	22.6 c	7.5 bc	87.5 ab
Manure veritcal mulch	59.4 ab	1.0 c	16.8 a	0.0 a	77.2 a	15.9 abc	78.4 abc
Manure only	68.3 ab	8.5 a	1.0 c	0.0 a	77.8 a	24.8 abc	70.2 abc
Manure + H ₂ SO ₄	70.8 a	0.6 c	5.4 bc	0.0 a	77.6 abc	26.4 bc	68.6 ab
Woodchips	50.5 abc	0.1 c	0.8 c	0.0 a	51.4 abc	6.6 abc	88.4 abc
Gypsum + CaCl ₂	51.0 abc	2.7 c	0.3 c	0.0 a	54.0 abc	21.0 abc	73.6 c
Gypsum + H ₂ SO ₄	71.9 a	1.9 c	0.8 c	0.0 a	74.6 a	32.6 a	62.4 c
Gypsum + H ₂ SO ₄ + irrigation	58.7 ab	1.4 c	0.7 c	0.0 a	60.8 ab	22.2 abc	72.8 abc
Topsoil only	33.8 bed	4.2 bc	2.7 bc	0.0 a	40.7 bc	5.6 bc	89.4 ab
Topsoil + irrigation	20.6 cd	6.3 ab	4.3 bc	0.2 a	31.2 bc	4.1 bc	90.9 ab

¹ Mean of three replications.

² Means within the plant class are significantly ($P \leq .05$) different if followed by a different letter.

APPENDIX B

Minesoil Physical and Chemical Data

Table 47. Fall, 1986 minesoil chemical analysis at the Belle Fourche site.

<u>TREATMENT</u> ¹	<u>BLOCK</u>	<u>DEPTH</u> ²	<u>pH</u>	<u>EC</u> <u>(mmhos/cm)</u>	<u>SAR</u>
1	1	1	7.8	11.8	30.3
1	1	2	6.7	11.2	32.1
1	1	3	6.4	9.6	29.1
1	1	4	6.4	8.0	24.5
1	1	5	7.6	8.8	25.1
1	1	6	7.4	11.1	31.4
2	1	1	7.3	10.9	23.9
2	1	2	6.8	22.0	32.0
2	1	3	7.1	10.4	28.1
2	1	4	6.9	8.6	23.6
2	1	5	7.2	8.9	21.4
2	1	6	7.0	7.2	26.1
1	2	1	7.1	11.3	32.4
1	2	2	6.8	11.8	34.9
1	2	3	6.6	10.6	29.8
1	2	4	7.6	7.1	31.6
1	2	5	7.0	12.2	32.5
1	2	6	8.1	8.8	23.2
2	2	1	7.0	21.1	20.6
2	2	2	7.0	19.22	26.6
2	2	3	6.9	12.7	33.9
2	2	4	7.7	7.8	29.6
2	2	5	7.2	9.7	23.2
2	2	6	7.4	8.4	23.2
1	3	1	7.5	10.4	29.4
1	3	2	7.1	9.9	28.0
1	3	3	6.9	8.5	26.4
1	3	4	7.4	11.7	32.0
1	3	5	7.1	8.2	34.0
1	3	6	8.4	6.6	24.3
2	3	1	7.2	19.0	16.9
2	3	2	6.8	16.3	37.0
2	3	3	7.3	14.2	39.5
2	3	4	6.9	6.5	52.5
2	3	5	6.7	9.1	30.1
2	3	6	7.3	8.2	23.1

¹ - Treatment 1 is phosphogypsum. Treatment 2 is magnesium chloride brine.

² - Depth 1 is 0-5cm, depth 2 is 5-10cm, depth 3 is 10-20cm, depth 4 is 20-35cm, depth 5 is 35-70cm, depth 6 is 70-140cm.

Table 48. Summer, 1987 physicochemical analysis at the Belle Fourche site.

<u>TREATMENT</u> ¹	<u>BLOCK</u>	<u>DEPTH</u> ²	<u>pH</u>	<u>EC</u> <u>(mmhos/cm)</u>	<u>SAR</u>	<u>SATURATION</u> <u>PERCENTAGE</u>
1	1	1	6.9	8.8	22.0	105
1	1	2	6.9	11.4	27.6	101
1	1	3	7.2	11.8	27.8	125
1	1	4	7.1	10.2	36.4	136
1	1	5	6.8	8.9	25.6	114
1	1	6	7.6	11.0	23.6	99
2	1	1	7.3	11.2	17.0	77
2	1	2	7.4	11.4	18.6	75
2	1	3	7.0	13.8	23.4	69
2	1	4	6.9	11.2	37.4	119
2	1	5	7.1	13.1	32.3	110
2	1	6	7.3	9.3	21.0	96
1	2	1	7.6	11.3	26.7	109
1	2	2	7.0	12.7	34.5	127
1	2	3	7.7	10.5	27.6	141
1	2	4	7.6	8.9	25.3	135
1	2	5	7.5	10.3	22.5	100
1	2	6	7.2	11.8	23.5	98
2	2	1	6.9	22.1	22.8	62
2	2	2	7.3	14.2	28.9	81
2	2	3	7.5	10.1	27.7	110
2	2	4	7.1	14.8	32.7	85
2	2	5	6.8	12.7	28.5	74
2	2	6	7.0	9.6	21.6	88
1	3	1	8.0	10.1	24.9	97
1	3	2	8.0	10.7	25.8	106
1	3	3	7.7	12.7	29.8	119
1	3	4	7.4	11.0	21.9	97
1	3	5	7.8	10.0	18.5	101
1	3	6	7.8	9.7	20.5	142
2	3	1	6.8	14.3	24.2	82
2	3	2	6.4	16.6	31.5	86
2	3	3	6.8	14.5	28.0	92
2	3	4	6.7	12.7	25.2	81
2	3	5	7.0	9.5	16.2	97
2	3	6	7.5	7.5	16.8	103

¹ - Treatment 1 is phosphogypsum. Treatment 2 is magnesium chloride brine.

² - Depth 1 is 0-5cm, depth 2 is 5-10cm, depth 3 is 10-20cm, depth 4 is 20-35cm, depth 5 is 35-70cm, depth 6 is 70-140cm.

